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HIGH CAPACITY WIRELESS COMMUNICATION USING SPATIAL SUBCHANNELS

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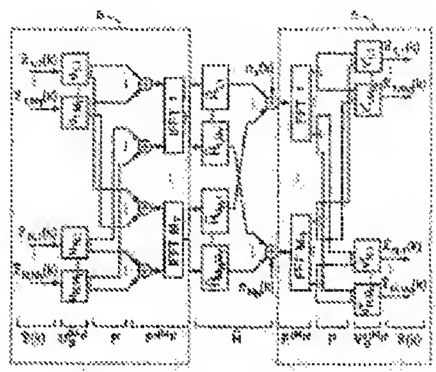
Abstract of **WO 9809381 (A1)**

In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix H couples an adaptive array of Mt antenna elements (1-Mt) at the base station (B) with an adaptive array Mr antenna elements (1-Mr) at the subscriber unit (S). The method comprises the step of determining from the channel matrix H a number L of independent spatio-temporal subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have Mt complex valued components and are selected to transmit distinct signal information in parallel over the independent subchannels, thereby providing increased communication capacity between the base and the subscriber. The sequence of transmitted signal vectors is transmitted from the base station array (1-Mt), and a sequence of received signal vectors is received at the subscriber array (1-Mr) and are decoded to yield the original information signals. Specific spatio-temporal coding techniques are described that increase system performance.



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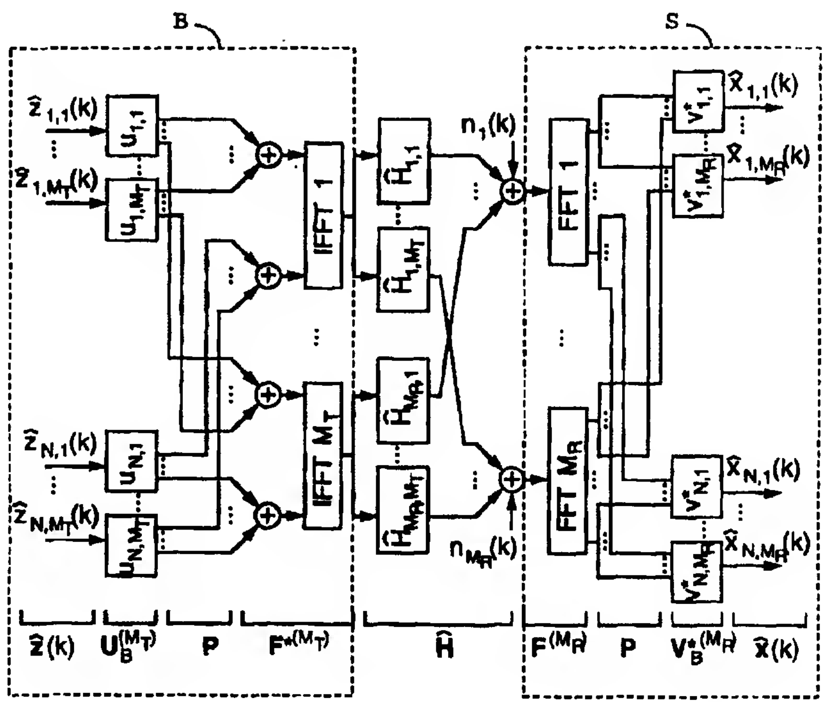
(57) Abstract



In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix H couples an adaptive array of Mt antenna elements (1-Mt) at the base station (B) with an adaptive array Mr antenna elements (1-Mr) at the subscriber unit (S). The method comprises the step of determining from the channel matrix H a number L of independent spatio-temporal subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have Mt complex valued components and are selected to transmit distinct signal information in parallel over the independent subchannels, thereby providing increased communication capacity between the base and the subscriber. The sequence of transmitted signal vectors is transmitted from the base station array (1-Mt), and a sequence of received signal vectors is received at the subscriber array (1-Mr) and are decoded to yield the original information signals. Specific spatio-temporal coding techniques are described that increase system performance.

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High Capacity Wireless Communication Using Spatial Subchannels

RELATED APPLICATIONS

This application claims priority from U.S. provisional applications 60/025,227 and 60/025,228, both filed 08/29/96. Both applications are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to digital wireless communication systems. More particularly, it relates to using antenna arrays by both a base station and a subscriber to significantly increase the capacity of wireless communication systems.

BACKGROUND OF THE INVENTION

Due to the increasing demand for wireless communication, it has become necessary to develop techniques for more efficiently using the allocated frequency bands, i.e. increasing the capacity to communicate information within a limited available bandwidth. This increased capacity can be used to enhance system performance by increasing the number of information channels, by increasing the channel information rates and/or by increasing the channel reliability.

FIG. 1 shows a conventional low capacity wireless communication system. Information is transmitted from a base station B to subscribers $S_1, \ldots, S_9$ by broadcasting omnidirectional signals on one of several predetermined frequency channels. Similarly, the subscribers transmit information back to the base station by broadcasting similar signals on one of the frequency channels. In this system, multiple users independently access the system through the

division of the frequency band into distinct subband frequency channels. This technique is known as frequency division multiple access (FDMA).

A standard technique used by commercial wireless phone systems to increasing capacity is to divide the service region into spatial cells, as shown in FIG. 2. Instead of using just one base station to serve all users in the region, a collection of base stations $B_1, \ldots, B_7$ are used to independently service separate spatial cells. In such a cellular system, multiple users can reuse the same frequency channel without interfering with each other, provided they access the system from different spatial cells. The cellular concept, therefore, is a simple type of spatial division multiple access (SDMA).

In the case of digital communication, additional techniques can be used to increase capacity. A few well known examples are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA allows several users to share a single frequency channel by assigning their data to distinct time slots. CDMA is normally a spread-spectrum technique that does not limit individual signals to narrow frequency channels but spreads them throughout the frequency spectrum of the entire band. Signals sharing the band are distinguished by assigning them different orthogonal digital code sequences. These techniques use digital coding to make more efficient use of the available spectrum.

Wireless systems may also use combinations of the above techniques to increase capacity, e.g. FDMA/CDMA and TDMA/CDMA. Although these and other known techniques increase the capacity of wireless communication systems, there is still a need to further increase system performance. Recently, considerable attention has focused on ways to increasing capacity by further exploiting the spatial domain.

One well-known SDMA technique is to provide the base station with a set of independently controlled directional antennas, thereby dividing the cell into separate sectors, each controlled by a separate antenna. As a result, the frequency reuse in the system can be increased and/or cochannel interference can be reduced. Instead of independently controlled directional antennas, this technique can also be implemented with a coherently controlled antenna array, as shown in FIG. 3. Using a signal processor to control the relative phases of the signals applied to the antenna elements, predetermined beams can be formed in the directions of the separate sectors. Similar signal processing can be used to selectively receive signals only from within the distinct sectors.

In an environment containing a significant number of reflectors (such as buildings), a signal will often follow multiple paths. Because multipath reflections alter the signal directions, the cell space experiences angular mixing and can not be sharply divided into distinct sectors. Multipath can therefore cause cochannel interference between sectors, reducing the benefit of sectoring the cell. In addition, because the separate parts of such a multipath signal can arrive with different phases that destructively interfere, multipath can result in unpredictable signal fading.

In order to avoid the above problems with multipath, more sophisticated SDMA techniques have been proposed. For example, U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al. disclose wireless communication systems that increase performance by exploiting the spatial domain. In the downlink, the base station determines the spatial channel of each subscriber and uses this channel information to adaptively control its antenna array to form customized beams, as shown in FIG. 4A. These beams transmit an information

signal x over multiple paths so that the signal x arrives to the subscriber with maximum strength. The beams can also be selected to direct nulls to other subscribers so that cochannel interference is reduced. In the uplink, as shown in FIG. 4B, the base station uses the channel information to spatially filter the received signals so that the transmitted signal x' is received with maximum sensitivity and distinguished from the signals transmitted by other subscribers. In this approach the same information signal follows several paths, providing increased spatial redundancy.

In the uplink, there are well known signal processing techniques for estimating the spatial channel from the signals received at the base station antenna array, e.g. by using *a priori* spatial or temporal structures present in the signal, or by blind adaptive estimation. If the uplink and downlink frequencies are the same, then the spatial channel for the downlink is directly related to the spatial channel for the uplink, and the base can use the known uplink channel information to perform transmit beamforming in the downlink. Because the spatial channel is frequency dependent and the uplink and downlink frequencies are often different, the base does not always have sufficient information to derive the downlink spatial channel information. One technique for obtaining downlink channel information is for the subscriber to periodically transmit test signals to the base on the downlink frequency rather than the uplink frequency. Another technique is for the base to transmit test signals and for the subscriber to feedback channel information to the base. If the spatial channel is quickly changing due to the relative movement of the base, the subscriber and/or reflectors in the environment, then the spatial channel must be updated frequently, placing a heavy demand on the system. One method to reduce the required feedback rates is to track only the subspace spanned by the time-averaged channel vector, rather than the instantaneous channel vector. Even with this

reduction, however, the required feedback rates are still a large fraction of the signal information rate.

Although these adaptive beamforming techniques require substantial signal processing and/or large feedback rates to determine the spatial channel in real time, these techniques have the advantage that they can navigate the complex spatial environment and avoid, to some extent, the problems introduced by multipath reflections. As a result, an increase in performance is enjoyed by adaptive antenna array systems, due to their use of the spatial dimension. Note, however, that while the base station antenna array can make efficient use of the spatial dimension by selectively directing the downlink signal to the subscriber S, the uplink signal in these systems is spatially inefficient. Typically, the subscriber is equipped with only a single antenna that radiates signal energy in all directions, potentially causing cochannel interference. These communication systems, therefore, do not make optimal use of the spatial dimension to increase capacity.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a communication system that significantly increases the capacity and performance of wireless communication systems by taking maximum advantage of the spatial domain. Another object of the invention is to provide computationally efficient coding techniques that make optimal use of the spatial dimensions of the channel. These and other objects and advantages will become apparent from the following description and associated drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a method of digital wireless communication that takes maximal advantage of spatial channel dimensions between a base station and a subscriber unit to increase system capacity and performance.

Surprisingly, the techniques of the present invention provide an increased information capacity in multipath environments. In contrast, known techniques suffer in the presence of multipath and do not exploit multipath to directly increase system capacity. In brief, the present invention teaches a method of wireless communication using antenna arrays at both the base and subscriber units to transmit distinct information signals over different spatial channels in parallel, thereby multiplying the capacity between the base and the subscriber. The present invention also teaches specific spatio-temporal coding techniques that make optimal use of these additional spatial subchannels.

Generally, the present invention provides a method of digital wireless communication between a base station and a subscriber unit, where a spatial channel characterized by a channel matrix **H** couples an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit. The method comprises the step of determining from the channel matrix **H** a number L of independent spatial subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have M_T complex valued components and are selected to distribute distinct signal information over the independent spatial subchannels. The sequence of transmitted signal vectors is transmitted from the array of M_T antenna elements at the base station, and a sequence of received signal vectors is received at the array of M_R antenna elements at the subscriber unit. The received signal vectors have M_R complex valued components. These received signal vectors are decoded to yield the information signals.

In another aspect, the invention provides a method that comprises computing from a set of K original information signals a spatio-temporal coded signal in accordance with a channel matrix **H**. The channel matrix **H** represents the spatio-temporal characteristics of the information link between a

base station array of M_T antenna elements and a subscriber unit array of M_R antenna elements. Signal processing techniques are used to decompose **H** into K parallel spatio-temporal subchannels that can independently carry information signals between the base and subscriber units. After transmitting the spatio-temporal coded signal over the channel, it is decoded into a set of K received information signals that correspond to the K original information signals. In a preferred embodiment, the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are derived from a decomposition of **H** into independent modes, and a set of K corresponding receive sequences. For example, the K spatio-temporal transmission sequences may be multiples of right singular vectors of **H**, and the receive sequences may be a matched set of K spatio-temporal filter sequences that are left singular vectors of **H**.

If L is the number of multipath components between the base station and the subscriber unit, then the number K of parallel spatio-temporal channels is not more than $(N+\nu) \times M_R$, not more than $N \times M_T$, and not more than $N \times L$, where $(N+\nu)$ is a maximum number of nonzero output samples transmitted for a block of N symbols. In a preferred embodiment, the original information signals comprise K blocks of N symbols, and the channel matrix **H** comprises $M_T \times M_R$ blocks of $N \times (N+\nu)$ channel matrices $\mathbf{H}_{ij}$.

In some applications of the present invention, the channel state information (CSI) may not be completely known, or may be expensive to compute. Accordingly, the present invention also provides a method for facilitating the efficient computation of the K received information signals from the transmitted spatio-temporal coded signal by adding cyclic prefixes to the coded signal prior to transmission.

DESCRIPTION OF THE FIGURES

FIG. 1 shows a low capacity wireless communication system well known in the prior art.

FIG. 2 illustrates a known technique of spatially dividing a service region into cells in order to increase system capacity.

FIG. 3 illustrates the use of beamforming with an antenna array to divide a cell into angular sectors, as is known in the art.

FIGS. 4A and 4B illustrate state-of-the-art techniques using adaptive antenna arrays for downlink and uplink beamforming, respectively.

FIGS. 5A and 5B show the parallel transmission of distinct information signals using spatial subchannels in downlink and uplink, respectively, as taught by the present invention.

FIGS. 6A and 6B are physical and schematic representations, respectively, of a communication channel for a system with multiple transmitting antennas and multiple receiving antennas, according to the present invention.

FIG. 7 is a block diagram of the system architecture for communicating information over a multiple-input-multiple-output spatial channel according to the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

As discussed above in relation to FIGS. 4A and 4B, prior art wireless systems employing an adaptive antenna array at the

base station are multiple-input-single-output (MISO) systems, i.e. the channel from the base to the subscriber is characterized by multiple inputs at the transmitting antenna array and a single output at the receiving subscriber antenna. Because these MISO systems can exploit some of the spatial channel, they have an increased capacity as compared to single-input-single-output (SISO) systems that are discussed above in relation to FIGS. 1 and 2. It should be noted that although the MISO systems disclosed in the prior art provide an increase in overall system capacity by spatially isolating separate subscribers from each other, these systems do not provide an increase in the capacity of information transmitted from the base to a single subscriber, or vice versa. As shown in FIGS. 4A and 4B, only one information signal is transmitted between the base and subscriber in both downlink and uplink of a MISO system. Even in the case where the subscriber is provided with an antenna array, the prior art suggests only that this capability would further reduce cochannel interference. Although the overall system capacity could be increased, this would not increase the capacity between the base and a single subscriber.

The present invention, in contrast, is a multiple-input-multiple-output (MIMO) wireless communication system that is distinguished by the fact that it increases the capacity of both uplink and downlink transmissions between a base and a subscriber through a novel use of additional spatial channel dimensions. The present inventors have recognized the possibility of exploiting multiple parallel spatial subchannels between a base station and a subscriber, thereby making use of additional spatial dimensions to increase the capacity of wireless communication. Surprisingly, this technique provides an increased information capacity and performance in multipath environments, a result that is in striking contrast with conventional wisdom.

FIGS. 5A and 5B illustrate a MIMO wireless communication system according to the present invention. As shown in FIG. 5A, a base station B uses adaptive antenna arrays and spatial processing to transmit distinct downlink signals x_1, x_2, x_3 through separate spatial subchannels to a subscriber unit S which uses an adaptive array and spatial processing to receive the separate signals. In a similar manner, the subscriber S uses an adaptive array to transmit distinct uplink signals x'_1, x'_2, x'_3 to the base B over the same spatial subchannels. As the multipath in the environment increases, the channel acquires a richer spatial structure that allows more subchannels to be used for increased capacity.

It is important to note that the simple assignment of the distinct signals to the distinct spatial paths in a one-to-one correspondence, as illustrated above, is only one possible way to exploit the additional capacity provided by the spatial subchannel structure. For example, coding techniques can be used to mix the signal information among the various paths. In addition, the present inventors have developed techniques for coupling these additional spatial dimensions to available temporal and/or frequency dimensions prior to transmission. Although such coupled spatio-temporal coding techniques are more subtle than direct spatial coding alone, they provide better system performance, as will be described in detail below.

In order to facilitate an understanding of the present invention and enable those skilled in the art to practice it, the following description includes a teaching of the general principles of the invention, as well as implementation details. First we develop a compact model for understanding frequency dispersive, spatially selective wireless MIMO channels. We then discuss their theoretical information capacity limits, and propose spatio-temporal coding structures that asymptotically achieve theoretical channel capacity. In particular, a spatio-temporal vector coding (STVC) structure

for burst transmission is disclosed, as well as a more practical, reduced complexity, discrete matrix multitone (DMMT) space-frequency coding structure. Both STVC and DMMT are shown to achieve the theoretical channel capacity as the burst duration increases.

In its preferred implementations, the present invention makes use of many techniques and devices well known in the art of adaptive antenna arrays systems and associated digital beamforming signal processing. These techniques and devices are described in detail in U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al., which are all incorporated herein by reference. In addition, a comprehensive treatment of the present state of the art is given by John Livita and Titus Kwok-Yeung Lo in *Digital Beamforming in Wireless Communications* (Artech House Publishers, 1996). Accordingly, the following detailed description focuses upon the specific signal processing techniques which are required to enable those skilled in the art to practice the present invention.

Consider a communication channel for a system with M_T transmitting antennas at a base B and M_R receiving antennas at a subscriber S, as illustrated in FIGS. 6A and 6B. The channel input at a sample time k can be represented by an M_T dimensional column vector

$$\mathbf{z}(k) = [z_1(k), \ldots, z_{M_T}(k)]^T,$$

and the channel output and noise for sample k can be represented, respectively, by M_R dimensional column vectors

$$\mathbf{x}(k) = [x_1(k), \ldots, x_{M_R}(k)]^T,$$

and

$$\mathbf{n}(k) = [n_1(k), \ldots, n_{M_R}(k)]^T.$$

The communication over the channel $\mathbf{H}$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{Hz}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix is

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & \cdots & h_{1,M_T} \\ \vdots & & \vdots \\ h_{M_R,1} & \cdots & h_{M_R,M_T} \end{pmatrix}.$$

Each matrix element h_{ij} represents the SISO channel between the i^{th} receiver antenna and the j^{th} transmitter antenna. Due to the multipath structure of the spatial channel, orthogonal spatial subchannels can be determined by calculating the independent modes (e.g. eigenvectors) of the channel matrix $\mathbf{H}$. These spatial subchannels can then be used to transmit independent signals and increase the capacity of the communication link between the base B and the subscriber S. Because the multipath introduces time delays, however, a spatial decomposition alone will result in temporal mixing of the signals. It is more appropriate, therefore, to perform a more general spatio-temporal analysis of the channel.

Let $\{z_j(n)\}$ be a digital symbol sequence to be transmitted from the j^{th} antenna element, $g(t)$ a pulse shaping function impulse response, and T the symbol period. Then the signal applied to the j^{th} antenna element at time t is given by

$$s_j(t) = \sum_n z_j(n) g(t-nT)$$

The pulse shaping function is typically the convolution of two separate filters, one at the transmitter and one at the receiver. The optimum receiver filter is a matched filter. In practice, the pulse shape is windowed resulting in a finite duration impulse response. We assume synchronous complex baseband sampling with symbol period T. We define n_0 and $(\nu+1)$

to be the maximum lag and length over all paths l for the windowed pulse function sequences $\{g(nT-\tau_l)\}$. To simplify notation, it is assumed that $n_0 = 0$, and the discrete-time notation $g(nT-\tau_l) = g_l(n)$ is adopted.

When a block of N data symbols are transmitted, N+ν non-zero output samples result beginning at time sample k-N+1 and ending with sample k+ν. The composite channel output can now be written as an $M_R \aleph (N+\nu)$ dimensional column vector with all time samples for a given receive antenna appearing in order so that

$$\mathbf{x}(k) = [x_1(k-N+1),\ldots,x_1(k+\nu),\ldots,x_{M_R}(k-N+1),\ldots,x_{M_R}(k+\nu)]^T,$$

with an identical stacking for the output noise samples $\mathbf{n}(k)$. Similarly, the channel input is an $M_T \aleph N$ dimensional column vector written as

$$\mathbf{z}(k) = [z_1(k-N+1),\ldots,z_1(k),\ldots,z_{M_T}(k-N+1),\ldots,z_{M_T}(k)]^T,$$

The spatio-temporal communication over the channel $\mathbf{H}$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{Hz}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_{1,1} & \cdots & \mathbf{H}_{1,M_T} \\ \vdots & & \vdots \\ \mathbf{H}_{M_R,1} & \cdots & \mathbf{H}_{M_R,M_T} \end{pmatrix}$$

is composed of SISO sub-blocks $\mathbf{H}_{ij}$ with each sub-block possessing the well known Toeplitz form.

We will now discuss the information capacity for the spatio-temporal channel developed above. The following analysis assumes that the noise $\mathbf{n}(k)$ is additive white Gaussian noise (AWGN) with covariance $\sigma^2\mathbf{I}$. Each channel use consists of an N

symbol burst transmission and the total average power radiated from all antennas and all time samples is constrained to less than a constant.

Write the singular value decomposition (SVD) of the channel matrix as $\mathbf{H}=\mathbf{V}_H\Lambda_H\mathbf{U}_H^*$, with the j^{th} singular value denoted $\lambda_{H,j}$. Write the spatio-temporal covariance matrix for $\mathbf{z}(k)$ as $\mathbf{R}_z$ with eigenvalue decomposition $\mathbf{R}_z=\mathbf{V}_Z\Lambda_Z\mathbf{U}_Z^*$, and eigenvalues $\lambda_{Z,j}$.

It can be demonstrated that the information capacity for the discrete-time spatio-temporal communication channel defined above is given by

$$C = \sum_{n=1}^{N\aleph M_T} \log \left(1 + \frac{\lambda_{Z,n}|\lambda_{H,n}|^2}{\sigma^2}\right),$$

where $\lambda_{Z,n}$ is given by the spatio-temporal water-filling solution. Motivated by this result, the inventors devised the following temporal vector coding technique. By appropriately selecting up to $N\aleph M_T$ spatio-temporal transmission vectors that are multiples of the right singular vectors of $\mathbf{H}$, and receiving with up to $N\aleph M_T$ matched spatio-temporal filter vectors that are the left singular vectors of $\mathbf{H}$, up to $N\aleph M_T$ parallel spatio-temporal subchannels are constructed for communicating information over the channel. Mathematically, this STVC channel is derived as follows. Substituting $\mathbf{H}=\mathbf{V}_H\Lambda_H\mathbf{U}_H^*$ into the original equation $\mathbf{x}(k)=\mathbf{H}\mathbf{z}(k)+\mathbf{n}(k)$ for the channel gives

$$\mathbf{x}(k) = \mathbf{V}_H\Lambda_H\mathbf{U}_H^*\mathbf{z}(k) + \mathbf{n}(k),$$

Left multiplication by $\mathbf{V}_H^*$ yields

$$\mathbf{V}_H^*\mathbf{x}(k) = \Lambda_H\mathbf{U}_H^*\mathbf{z}(k) + \mathbf{V}_H^*\mathbf{n}(k),$$

which yields the STVC channel when rewritten as

$\hat{\mathbf{x}}(k) = \Lambda_H \hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k)$,

where $\hat{\mathbf{z}}(k)=\mathbf{U}_H^{*}\mathbf{z}(k)$, $\hat{\mathbf{x}}(k)=\mathbf{V}_H^{*}\mathbf{x}(k)$ and $\hat{\mathbf{n}}(k)=\mathbf{V}_H^{*}\mathbf{n}(k)$.

By analyzing the ranks of the above matrices, it can be demonstrated that the maximum number of finite amplitude parallel spatio-temporal channel dimensions, K, that can be created to communicate over the far field channel defined above is equal to min { $N \aleph L$, $(N+\nu) \aleph M_R$, $N \aleph M$ }, where L is the number of multipath components. Thus, multipath is an advantage in far-field MIMO channels. If the multipath is large (L 1), the capacity can be multiplied by adding antennas to both sides of the radio link. This capacity improvement occurs with no penalty in average radiated power or frequency bandwidth because the number of parallel channel dimensions is increased. In practice, an adaptive antenna array base station, such as that described by Barratt et al., is modified to implement the above vector coding scheme. In particular, a signal processor is designed to perform a spatio-temporal transform of information signals in accordance with the above equations so that they may be transmitted through the independent parallel subchannels and decoded by the subscriber.

The space-time vector coding solution described above requires a computation of the singular value decomposition of an $(N+\nu) \aleph M_R \times N \aleph M_T$ matrix. Since this computation can be complex, the present inventors have developed an optimal space-time communication structure that requires less computational complexity to implement. In particular, complexity can be reduced by using a coding structure similar to the discrete multi-tone (DMT) standard. DMT is in widespread use for wired SISO channels. DMT has also been applied to wired MISO channels, as described in U.S. Pat. No. 5,625,651 which is hereby incorporated by reference. The present inventors have generalized DMT to the MIMO case and

adapted it to wireless channels' to obtain a novel space-frequency coding structure that results in a matrix of transmission and reception vector solutions for each discrete Fourier transform (DFT) frequency index. Because this new coding scheme has been generalized to MIMO channels characterized by a channel matrix, it is called discrete matrix multi-tone (DMMT).

In DMMT, N data symbols are again transmitted during each channel usage. However, a cyclic prefix is added to the data so that the last ν data symbols are transmitted from each antenna element prior to transmitting the full block of N symbols. By receiving only N time samples at the output of each antenna element, ignoring the first and last ν output samples, the MIMO channel submatrices $\hat{\mathbf{H}}_{ij}$ now appear as cyclic structures:

$$\hat{\mathbf{H}}_{i,j} = \begin{pmatrix} h(\nu) & \ldots & h(0) & 0 & 0 & \ldots & 0 & 0 & 0 & 0 \\ 0 & h(\nu) & & h(0) & 0 & \ldots & 0 & 0 & 0 & 0 \\ \vdots & & & & \vdots & & \vdots & & & \vdots \\ 0 & & & & 0 & \ldots & 0 & & & 0 \\ 0 & \ldots & 0 & 0 & 0 & \ldots & 0 & h(\nu) & \ldots & h(0) \\ & & & \vdots & \vdots & & \vdots & & & \vdots \\ h(\nu-1) & \ldots & h(0) & 0 & 0 & \ldots & 0 & \ldots & 0 & h(\nu) \end{pmatrix}$$

Given the cyclic SISO channel blocks, the channel matrix can be diagonalized with a relatively simple three step procedure. First post multiply $\hat{\mathbf{H}}$ with the $N \aleph M_T \times N \aleph M_T$ block diagonal inverse discrete Fourier transform (IDFT) matrix $\mathbf{F}^{*(M_T)}$ where each diagonal block is the unitary $N \times N$ IDFT matrix $\mathbf{F}^*$. The next step is to premultiply $\hat{\mathbf{H}}$ by a similar $N \aleph M_R \times N \aleph M_R$ block diagonal DFT matrix $\mathbf{F}^{(M_R)}$ where the diagonal submatrices $\mathbf{F}$ are $N \times N$ DFT matrices. With the well known result that the discrete Fourier transform basis vectors form the orthonormal singular vectors of the cyclic matrices $\hat{\mathbf{H}}_{ij}$, the new channel

matrix resulting from the IDFT post multiplication and the DFT premultiplication is

$$\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)} = \begin{pmatrix} \Gamma_{1,1} & \cdots & \Gamma_{1,M_T} \\ \vdots & & \vdots \\ \Gamma_{M_R,1} & \cdots & \Gamma_{M_R,M_T} \end{pmatrix}$$

where $\Gamma_{i,j}$ is the diagonal matrix containing the singular values $\gamma_{i,j,n}$ of the cyclic channel submatrix $\hat{\mathbf{H}}_{ij}$. Premultiplication and postmultiplication by a permutation matrix $\mathbf{P}$ yields the block diagonal matrix

$$\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P} = \begin{pmatrix} \mathbf{B}_1 & & 0 \\ & \aleph . & \\ 0 & & \mathbf{B}_N \end{pmatrix}$$

where

$$\mathbf{B}_n = \begin{pmatrix} \gamma_{1,1,n} & \cdots & \gamma_{1,M_T,n} \\ \vdots & & \vdots \\ \gamma_{M_R,1,n} & \cdots & \gamma_{M_R,M_T,n} \end{pmatrix}$$

is the $M_R \times M_T$ space-frequency channel evaluated at DFT index n. Given the SVD of $\mathbf{B}_n = \mathbf{V}_{B,n}\Lambda_{B,n}\mathbf{U}^{*}_{B,n}$, the diagonal DMMT channel matrix $\hat{\mathbf{H}}$ is finally obtained by post multiplying by $\mathbf{U}_B^{(M_T)}$ and premultiplying by $\mathbf{V}_B^{*(M_R)}$ to obtain

$$\Lambda_{\hat{H}} = \mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)} = \begin{pmatrix} \Lambda_{\hat{H},1} & & 0 \\ & \aleph . & \\ 0 & & \Lambda_{\hat{H},N} \end{pmatrix}$$

where $\mathbf{U}_B^{(M_T)}$ is block diagonal containing the right singular matrices of the $\mathbf{B}_n$ matrices, $\mathbf{V}_B^{*(M_R)}$ is block diagonal containing the left singular matrices of the $\mathbf{B}_n$ matrices, and each of the diagonal submatrices $\Lambda_{\hat{H},n}$ contains the DMMT spatial sub-channel amplitudes, $\lambda_{\hat{H},n,j}$ for DFT bin n. The parallel channel DMMT equation is then

$$\hat{\mathbf{x}}(k) = \Lambda_{\hat{H}}\hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k),$$

where $\mathbf{z}(k)$ is the dimension $N \aleph M_T$ input symbol vector, $\hat{\mathbf{x}}(k)$ is the dimension $N \aleph M_R$ output symbol vector, and $\hat{\mathbf{n}}(k)$ is the dimension $N \aleph M_R$ equivalent output noise vector after the DFT and spatial orthogonalization operations are performed. A block diagram architecture that implements this DMMT space-frequency channel decomposition is presented in FIG. 7. The left portion of the diagram corresponds to the application of the operators $\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)}$ on the signal $\hat{\mathbf{z}}(k)$. These operations are performed by a signal processor at the transmitter. The right portion of the diagram corresponds to the application of the operators $\mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}$ on the received signals to recover a received information signal $\hat{\mathbf{x}}(k)$. These operations are performed by a signal processor at the receiver. The central matrix $\hat{\mathbf{H}}$ corresponds to the spatial channel itself. By construction, the signal processing operations result in a direct relationship between the received and transmitted information signals, as indicated by the fact that the matrix $\Lambda_{\hat{H}}$ in the parallel channel DMMT equation is diagonal.

This coding scheme significantly reduces the signal processing complexity required at the transmitter and receiver to diagonalize all space-time subchannels for each data block. In particular, this asymptotically optimal space-frequency MIMO DMMT information transmission technique has a complexity advantage of approximately N^2 as compared to the vector coding case. Moreover, since all of the matrix operations involved in creating the diagonal DMMT channel are invertible, the capacity of the DMMT channel is unchanged from that of the original cyclic sub-block matrix $\hat{\mathbf{H}}$. Thus, compared to STVC, the only capacity decrease for the DMMT space-time coding solution is due to the radiated power penalty required to transmit the cyclic prefix. This capacity penalty, however,

becomes small for large N. Thus, this new communications structure offers the advantage of very large increases in capacity without penalty in total average transmitted power or bandwidth.

In order to perform transmit beamforming, the base station signal processor computes spatio-temporal downlink subchannel information from downlink channel information fed back from the subscriber. The downlink signal information is then encoded in accordance with this computed downlink subchannel information. Similarly, the subscriber performs the same functions for the uplink channel using information fed back from the base. Because the present invention provides techniques for efficient channel estimation and increased channel capacity, the base and subscriber can both quickly estimate the channel and exchange channel information over the increased capacity channels, possibly at a rate slower than that of information data. As a result, both the base and subscriber can maintain a high degree of spatial resolution in transmit beamforming, thereby significantly reducing cochannel interference from other base stations or subscribers. As a result of this high degree of spatial discrimination in both transmission and reception, many more base stations and subscribers can share the same region of space while using the same frequency channel. Consequently, in addition to increasing the capacity of the channel between any two arrays, the present invention also increases system wide capacity by significantly reducing cochannel interference.

The teaching contained in this description can easily be extended to channels where the noise is not white but is highly structured as in the case of additive co-channel interference. In this case, large gains in cellular network capacity result from the ability to null interference at the receiver and the ability to constrain radiated interference power at the transmitter. These spatial coding techniques can also be applied to single frequency subchannel systems with

flat fading, conventional analog multicarrier transmission channels, or CDMA channels where each code delay can be decomposed into orthogonal subchannels provided that there is sub-chip multipath. The concepts of the present invention can also be applied to a more general class of channels where the antenna array is distributed over large distances and the propagation does not follow far field behavior. Finally, other communication media such as wire-line, acoustic media, and optical media will experience the same basic communication system benefits when spatio-temporal MIMO channel structures are employed. Thus, it will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A method of digital wireless communication between a base station and a subscriber unit, the method comprising:

determining from channel information a number L of independent spatial subchannels, wherein the channel information comprises spatial information relating to a spatial channel coupling an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit;

encoding a plurality of information signals into a sequence of transmitted signal vectors, wherein the transmitted signal vectors have M_T complex valued components and are selected to send distinct information signal over the independent spatial subchannels;

transmitting the sequence of transmitted signal vectors from the array of M_T antenna elements at the base station;

receiving a sequence of received signal vectors at the array of M_R antenna elements at the subscriber unit, wherein the received signal vectors have M_R complex valued components; and

decoding the received signal vectors to recover the information signals.

2. The method of claim 1 further comprising transmitting the channel information from the subscriber to the base.

3. The method of claim 1 wherein the channel information comprises a spatio-temporal channel matrix.

4. The method of claim 1 wherein the number L of independent spatial subchannels is equal to the number of multiple signal paths between the base and the subscriber.

5. The method of claim 1 wherein the encoding step comprises scaling the information signals by complex numbers,

permuting the scaled information signals and inverse Fourier transforming the permuted scaled information signals, and wherein the decoding step comprises Fourier transforming the received signals, permuting the Fourier transformed received signals, and scaling the permuted Fourier transformed received signals.

6. A method of digital wireless communication between a base station and a subscriber unit, the method comprising:

computing from a set of K original information signals a spatio-temporal coded signal in accordance with a channel matrix **H** having K parallel spatio-temporal subchannels;

transmitting the spatio-temporal coded signal from a base station array of M_T antenna elements through a channel corresponding to the channel matrix **H** to a subscriber unit array of M_R antenna elements; and

computing from the transmitted spatio-temporal coded signal a set of K received information signals.

7. The method of claim 6 wherein K is not more than $(N+v) \times M_R$, not more than $N \times M_T$, and not more than $N \times L$, where L is a maximum number of multipath components between the base station and the subscriber unit, and where $(N+v)$ is a maximum number of nonzero output samples transmitted for a block of N symbols.

8. The method of claim 6 wherein the original information signals comprise K blocks of N symbols, and the channel matrix **H** comprises $M_T \times M_R$ blocks of $N \times (N+v)$ channel matrices $\mathbf{H}_{ij}$, where $(N+v)$ is a maximum number of nonzero output samples transmitted for a block of N symbols.

9. The method of claim 6 wherein cyclic prefixes are added to the coded signal prior to the transmitting step, thereby facilitating the efficient computation of the K received information signals from the transmitted spatio-temporal coded signal.

10. The method of claim 6 wherein the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are derived from a decomposition of **H** into independent modes.

11. The method of claim 6 wherein the K parallel spatio-temporal subchannels are characterized by a set of K spatio-temporal transmission sequences that are multiples of right singular vectors of **H**, and matched set of K spatio-temporal filter sequences that are left singular vectors of **H**.

12. A digital wireless communication system comprising:

a base station comprising a base station antenna array and a base station signal processor coupled to the base station antenna array;

a subscriber unit comprising a subscriber antenna array coupled through a wireless channel to the base station antenna array and a subscriber signal processor coupled to the subscriber antenna array;

wherein the base station signal processor computes spatio-temporal downlink subchannel information from downlink channel information received from the subscriber, and encodes downlink signal information in accordance with the computed downlink subchannel information; and

wherein the subscriber signal processor computes spatio-temporal uplink subchannel information from uplink channel information received from the base station, and encodes uplink signal information in accordance with the computed uplink subchannel information.

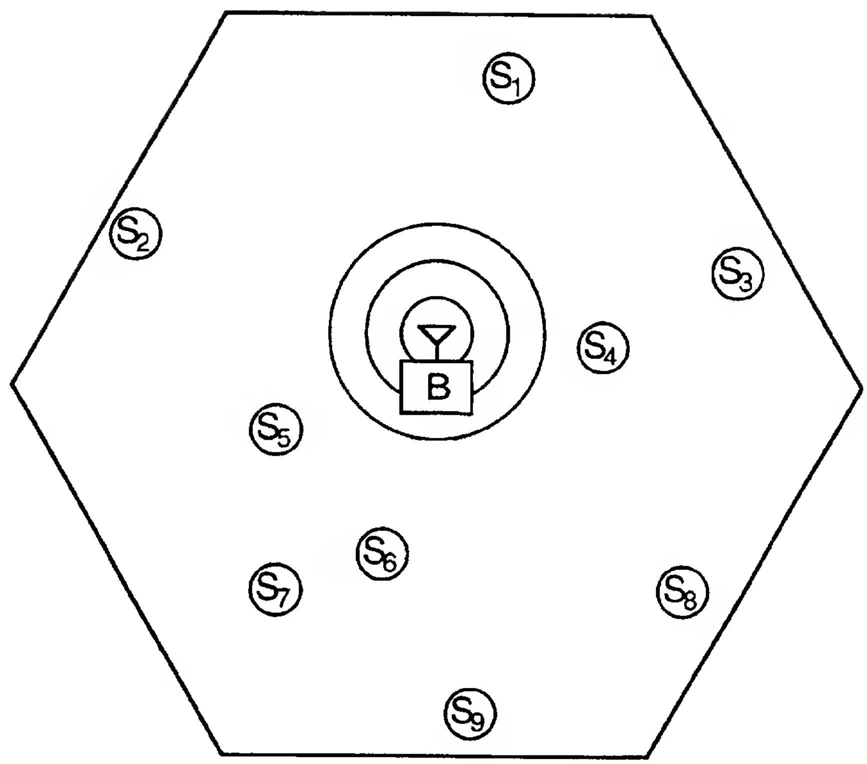

FIG. 1
(PRIOR ART)

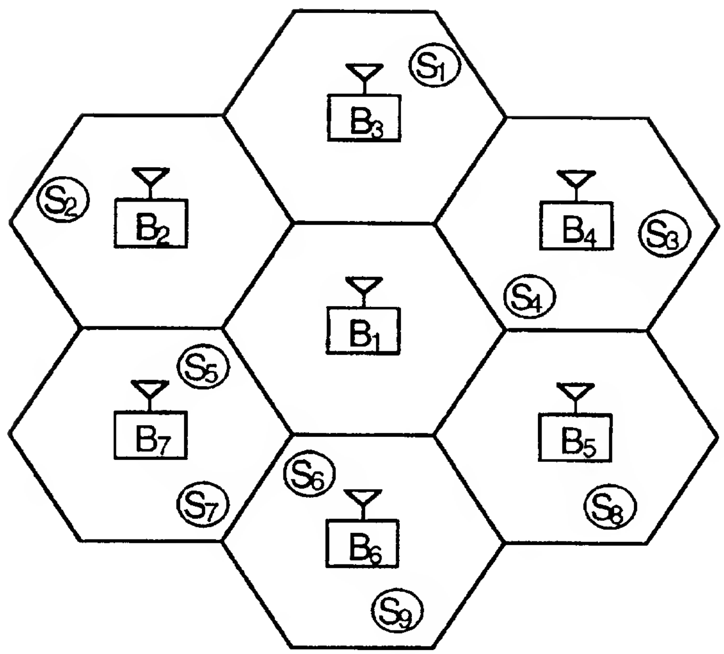

FIG. 2
(PRIOR ART)

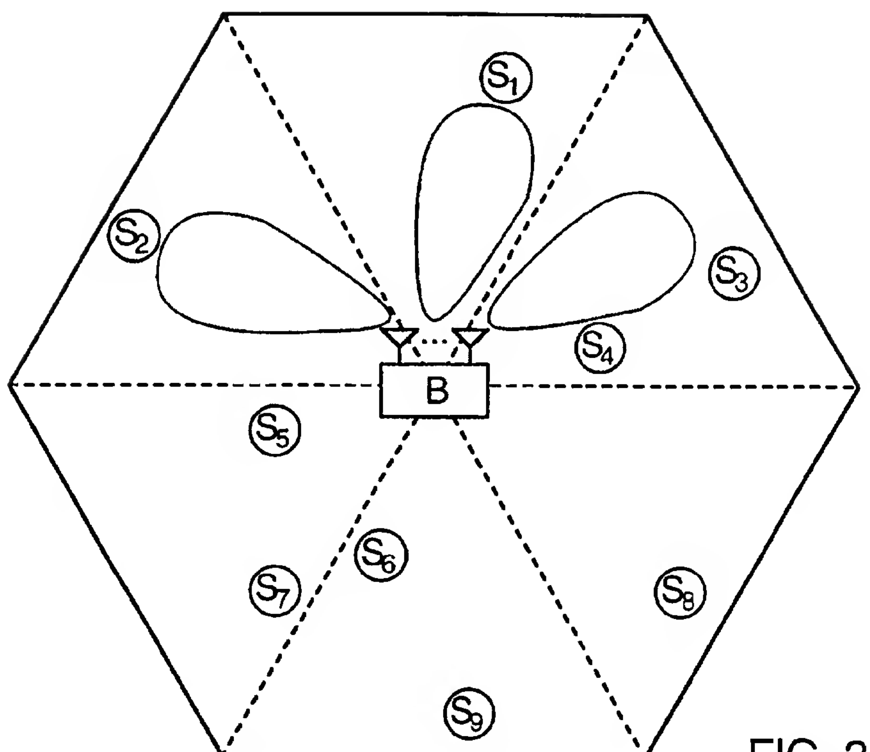

FIG. 3
(PRIOR ART)

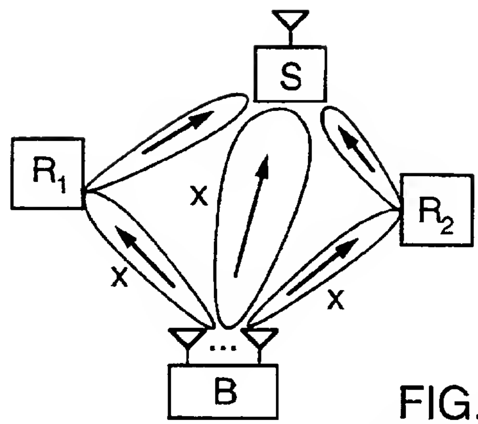

FIG. 4A
(PRIOR ART)

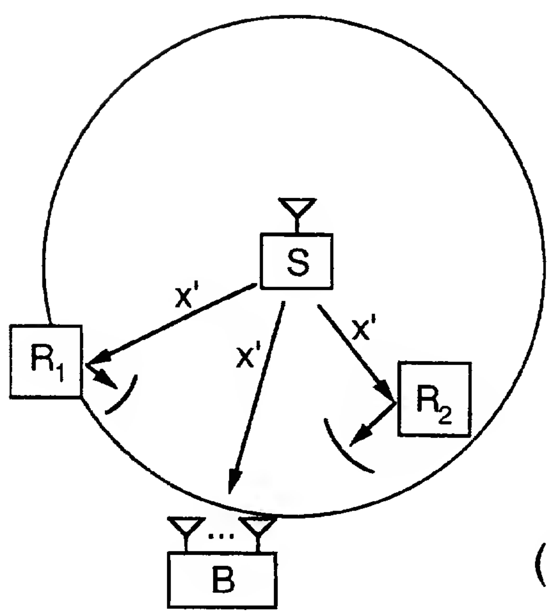

FIG. 4B
(PRIOR ART)

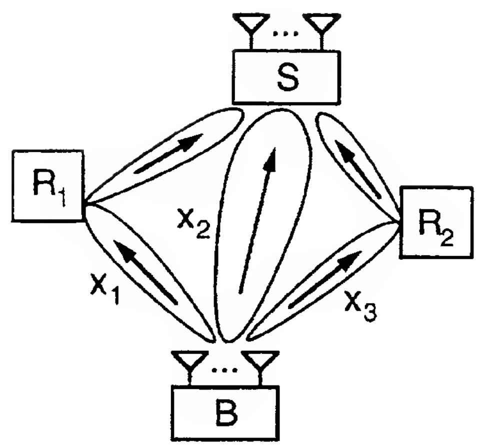

FIG. 5A

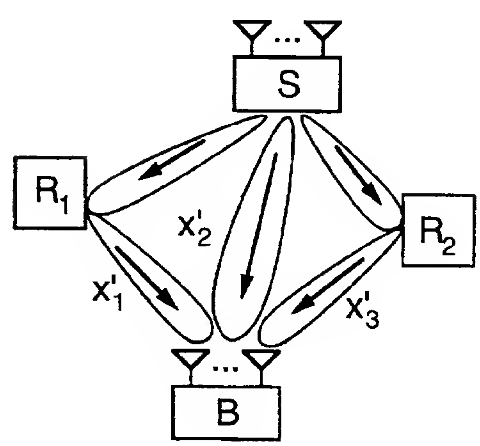

FIG. 5B

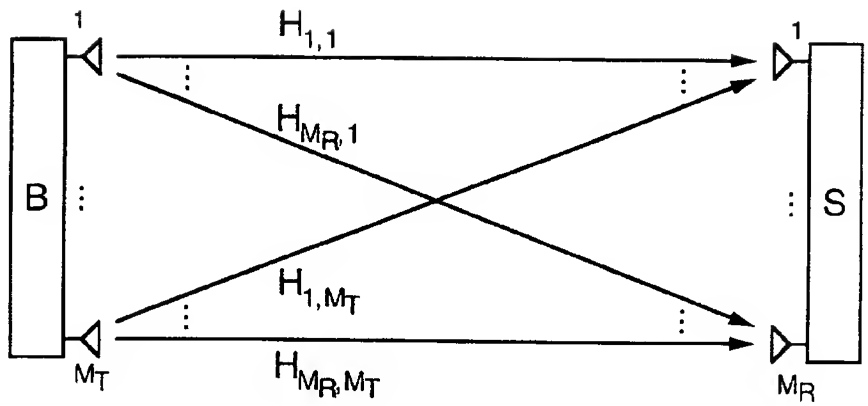
B
1
M_T
$H_{1,1}$
$H_{M_R,1}$
H_{1,M_T}
H_{M_R,M_T}
1
M_R
S

FIG. 6A

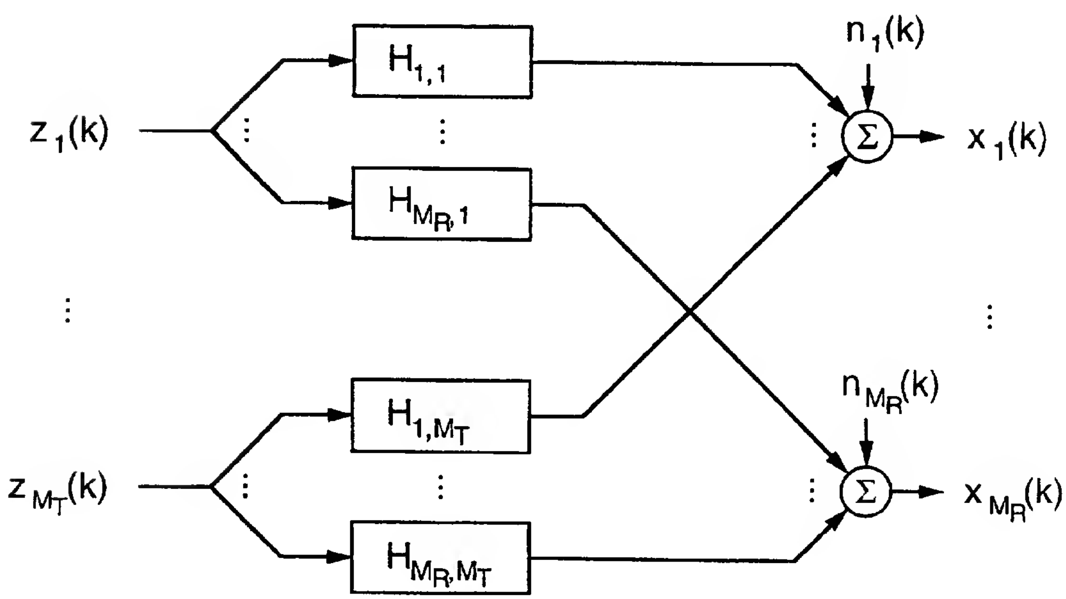
$z_1(k)$
$z_{M_T}(k)$
$H_{1,1}$
$H_{M_R,1}$
H_{1,M_T}
H_{M_R,M_T}
$n_1(k)$
$n_{M_R}(k)$
Σ
$x_1(k)$
$x_{M_R}(k)$

FIG. 6B

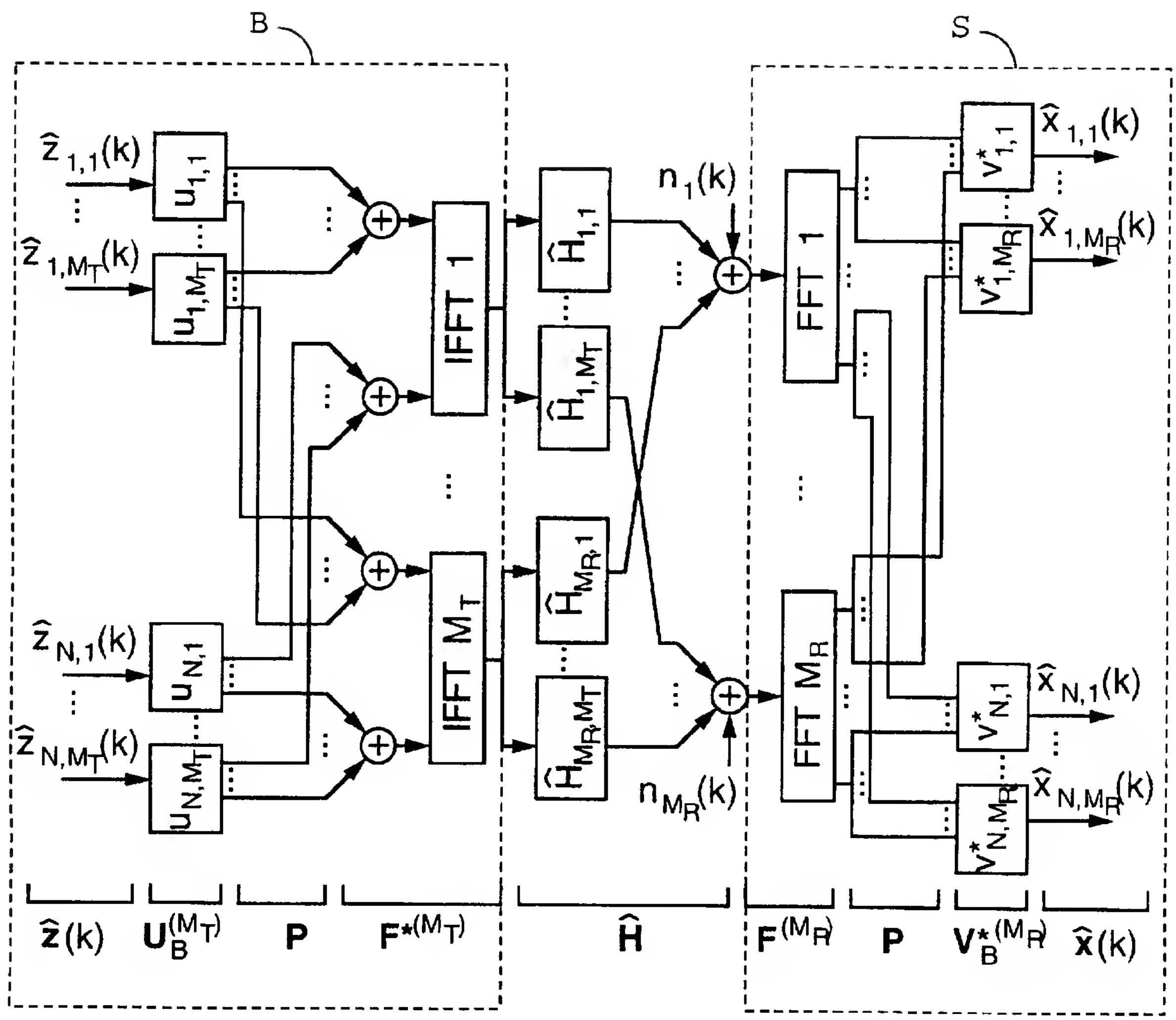
B
S
$\hat{z}_{1,1}(k)$
$\hat{z}_{1,M_T}(k)$
$\hat{z}_{N,1}(k)$
$\hat{z}_{N,M_T}(k)$
$u_{1,1}$
u_{1,M_T}
$u_{N,1}$
u_{N,M_T}
IFFT 1
IFFT M_T
$\hat{H}_{1,1}$
$\hat{H}_{1,M_T}$
$\hat{H}_{M_R,1}$
$\hat{H}_{M_R,M_T}$
$n_1(k)$
$n_{M_R}(k)$
FFT 1
FFT M_R
$v^*_{1,1}$
v^*_{1,M_R}
$v^*_{N,1}$
v^*_{N,M_R}
$\hat{x}_{1,1}(k)$
$\hat{x}_{1,M_R}(k)$
$\hat{x}_{N,1}(k)$
$\hat{x}_{N,M_R}(k)$
$\hat{\mathbf{z}}(k)$
$\mathbf{U}_B^{(M_T)}$
$\mathbf{P}$
$\mathbf{F}^{*(M_T)}$
$\hat{\mathbf{H}}$
$\mathbf{F}^{(M_R)}$
$\mathbf{P}$
$\mathbf{V}_B^{*(M_R)}$
$\hat{\mathbf{x}}(k)$

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/15363

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04B 1/38; H04M 1/00
US CL :455/562, 101, 103, 272
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/562, 101, 103, 272, 504, 506, 65, 132; 375/347

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,710,944 A (NOSSEN) 01 December 1987, columns 3-8, figures 1 and 5.	1-12
X	US 5,548,819 A (ROBB) 20 August 1996, columns 10-13, figures 1a-1b.	1-12
A,P	US 5,649,287 A (FORSSEN ET AL) 15 July 1997, figure 5.	1-12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 OCTOBER 1997	17 NOV 1997

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	NGUYEN VO Joni Hill
Facsimile No. (703) 305-3230	Telephone No. (703) 308-6728

US006058105A

United States Patent [19]

Hochwald et al.

[11] **Patent Number: 6,058,105**

[45] **Date of Patent: May 2, 2000**

[54] **MULTIPLE ANTENNA COMMUNICATION SYSTEM AND METHOD THEREOF**

[75] Inventors: **Bertrand M. Hochwald; Thomas Louis Marzetta**, both of Summit, N.J.

[73] Assignee: **Lucent Technologies Inc.**, Murray Hill, N.J.

[21] Appl. No.: **08/938,168**

[22] Filed: **Sep. 26, 1997**

[51] **Int. Cl.**[7] **H04B 1/02**; H04B 1/04; H04B 7/00

[52] **U.S. Cl.** **370/310**; 455/103; 342/367

[58] **Field of Search** 370/277, 280, 370/310, 326, 329, 334, 315, 316, 323, 325; 455/103, 132, 272, 562; 342/354, 367

[56] **References Cited**

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"Capacity of Multi–antenna Gaussian Channels," by I. Emre Telatar, *AT&T Bell Laboratories Technical Memorandum*, Document No. BL011217–950615–07TM, Nov. 13,1991.

U.S. Patent Application, "Wireless Communications System Having A Layered Space–Time Architecture Employing Multi–Element Antennas," Gerard J. Foschini, Filed Jul. 1, 1996, Serial No. 08/673981.

Primary Examiner—Michael Horabik
Assistant Examiner—Kevin C. Harper
Attorney, Agent, or Firm—Julio A. Garceran

[57] **ABSTRACT**

A communications system achieves high bit rates over an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, by creating virtual sub-channels from the actual communications channel. The multiple antenna system creates the virtual sub-channels from the actual communications channel by using propagation information characterizing the actual communications channel at the first and second units. For transmissions from the first unit to the second unit, the first unit sends a virtual transmitted signal over at least a subset of the virtual sub-channels using at least a portion of the propagation information. The second unit retrieves a corresponding virtual received signal from the same set of virtual sub-channels using at least another portion of said propagation information.

36 Claims, 5 Drawing Sheets

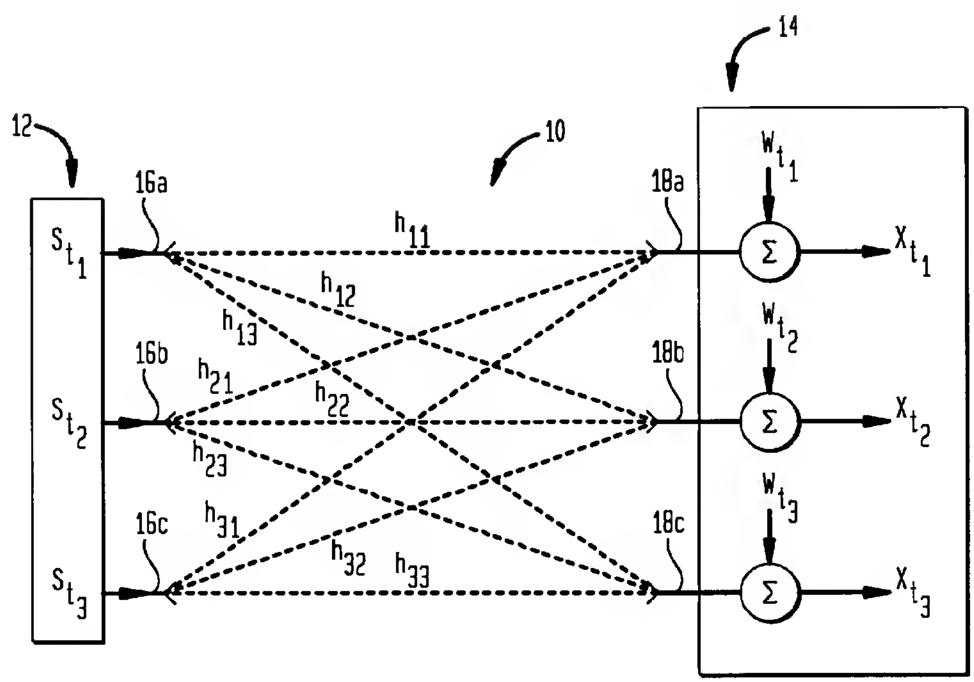


FIG. 1

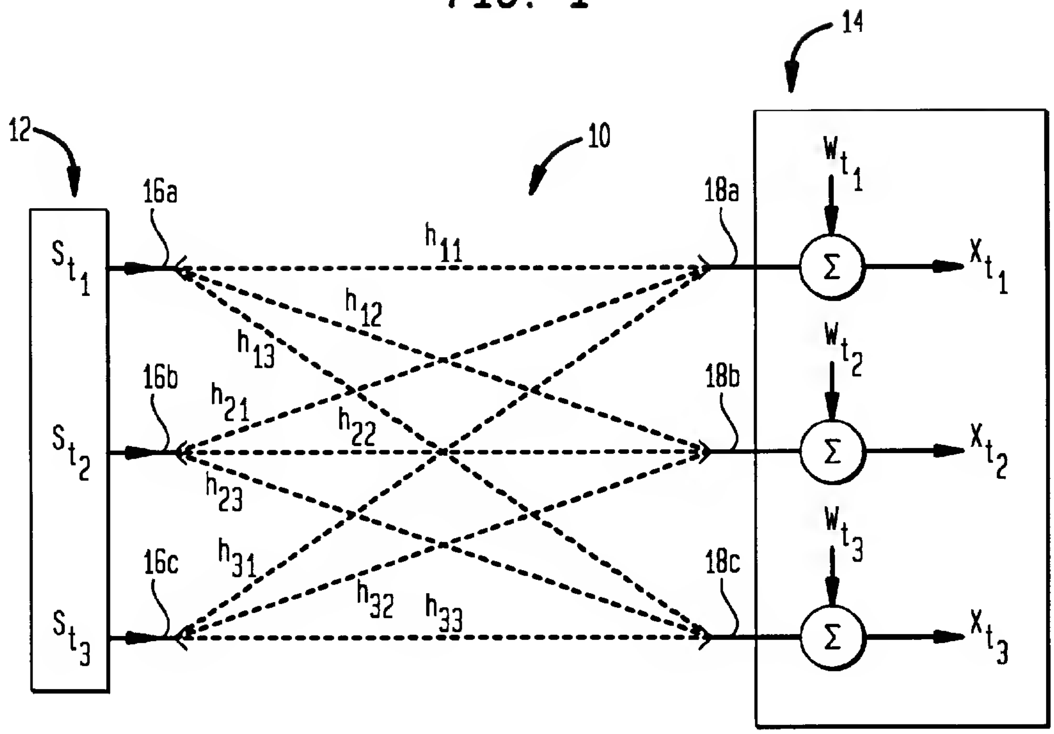

14
12
10
16a
18a
S_{t_1}
S_{t_2}
S_{t_3}
W_{t_1}
W_{t_2}
W_{t_3}
h_{11}
h_{12}
h_{13}
h_{21}
h_{22}
h_{23}
h_{31}
h_{32}
h_{33}
16b
16c
18b
18c
Σ
X_{t_1}
X_{t_2}
X_{t_3}

FIG. 2

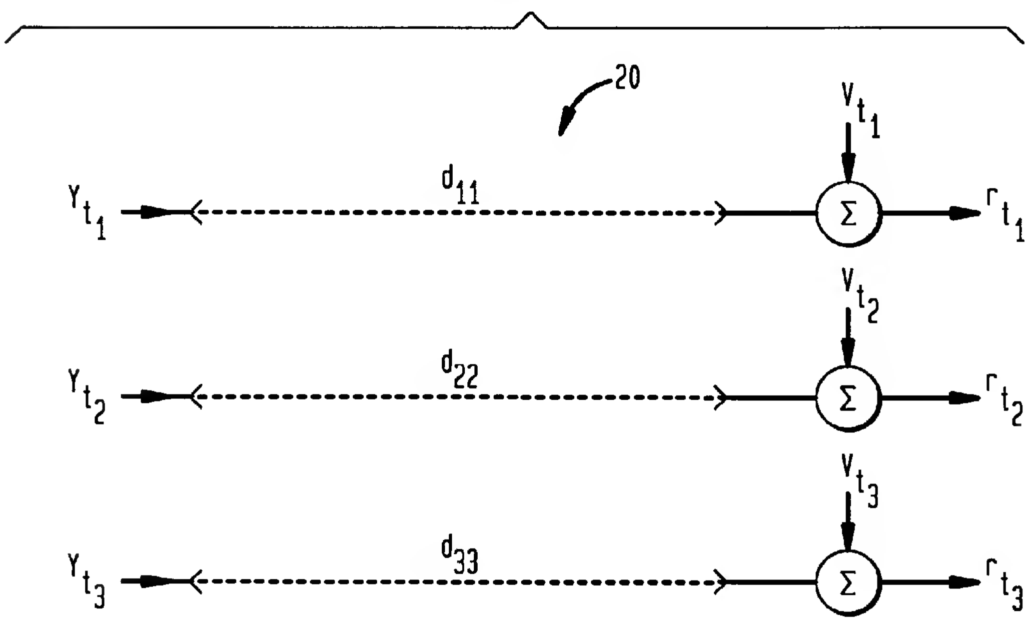

20
Y_{t_1}
Y_{t_2}
Y_{t_3}
d_{11}
d_{22}
d_{33}
V_{t_1}
V_{t_2}
V_{t_3}
Σ
r_{t_1}
r_{t_2}
r_{t_3}

FIG. 3

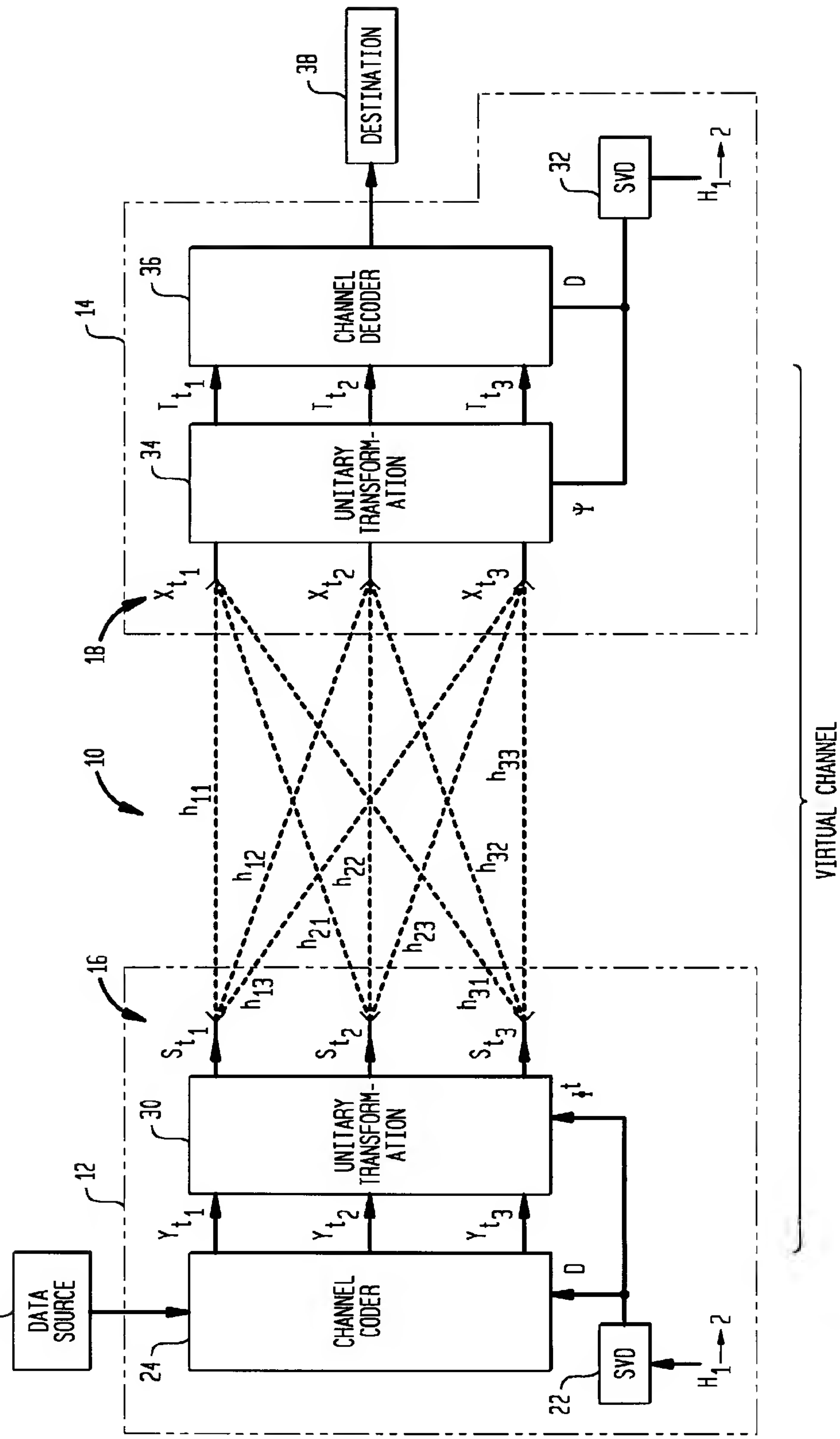

DATA SOURCE
28
CHANNEL CODER
24
12
UNITARY TRANSFORM-ATION
30
SVD
22
$H_{1\rightarrow 2}$
D
Φ^t
Y_{t_1}
Y_{t_2}
Y_{t_3}
S_{t_1}
S_{t_2}
S_{t_3}
16
10
h_{11}
h_{12}
h_{13}
h_{21}
h_{22}
h_{23}
h_{31}
h_{32}
h_{33}
18
X_{t_1}
X_{t_2}
X_{t_3}
UNITARY TRANSFORM-ATION
34
Ψ
T_{t_1}
T_{t_2}
T_{t_3}
CHANNEL DECODER
36
14
D
SVD
32
$H_{1\rightarrow 2}$
DESTINATION
38
VIRTUAL CHANNEL

FIG. 4

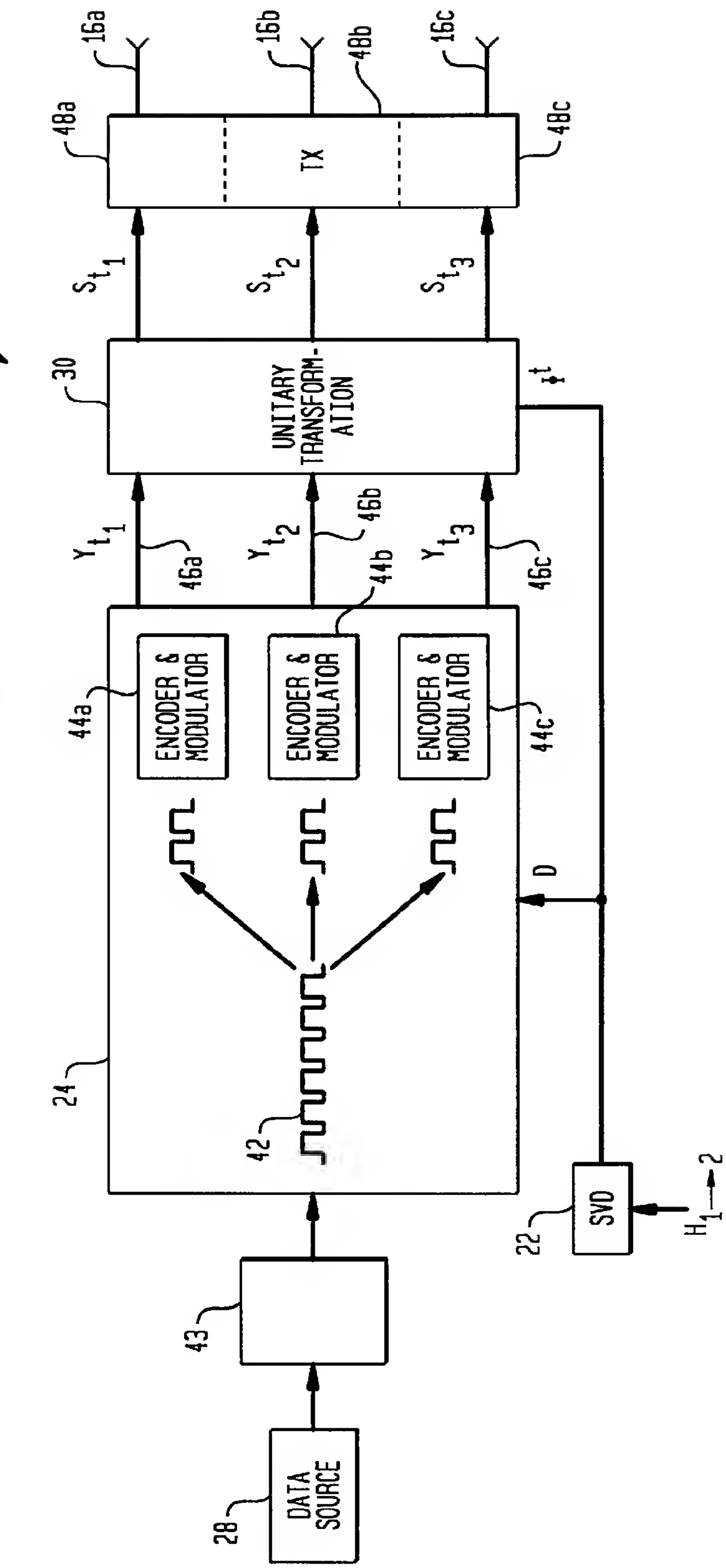
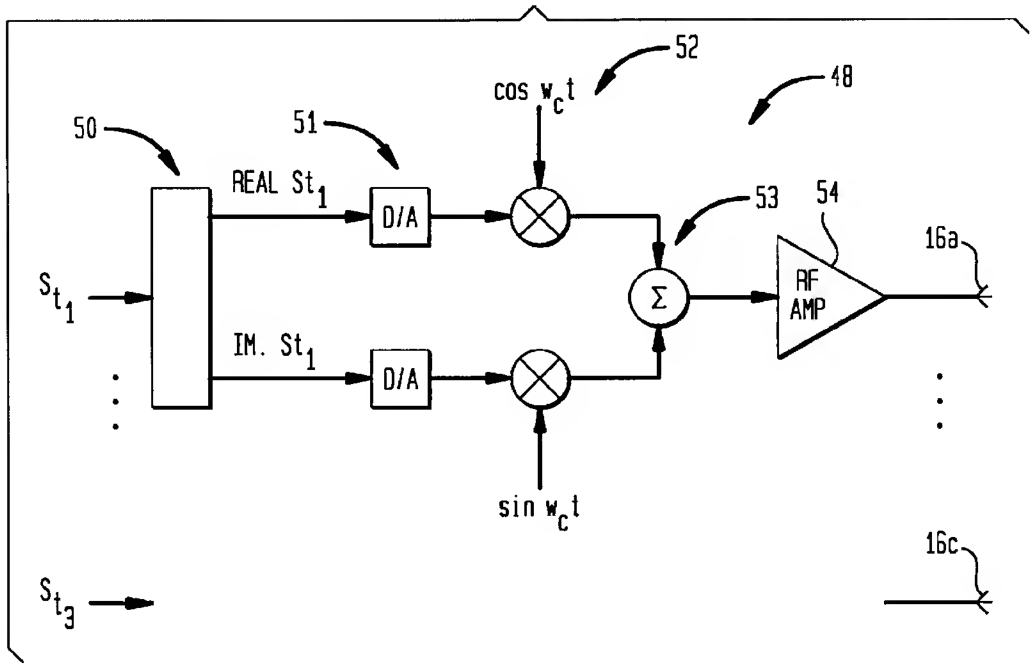
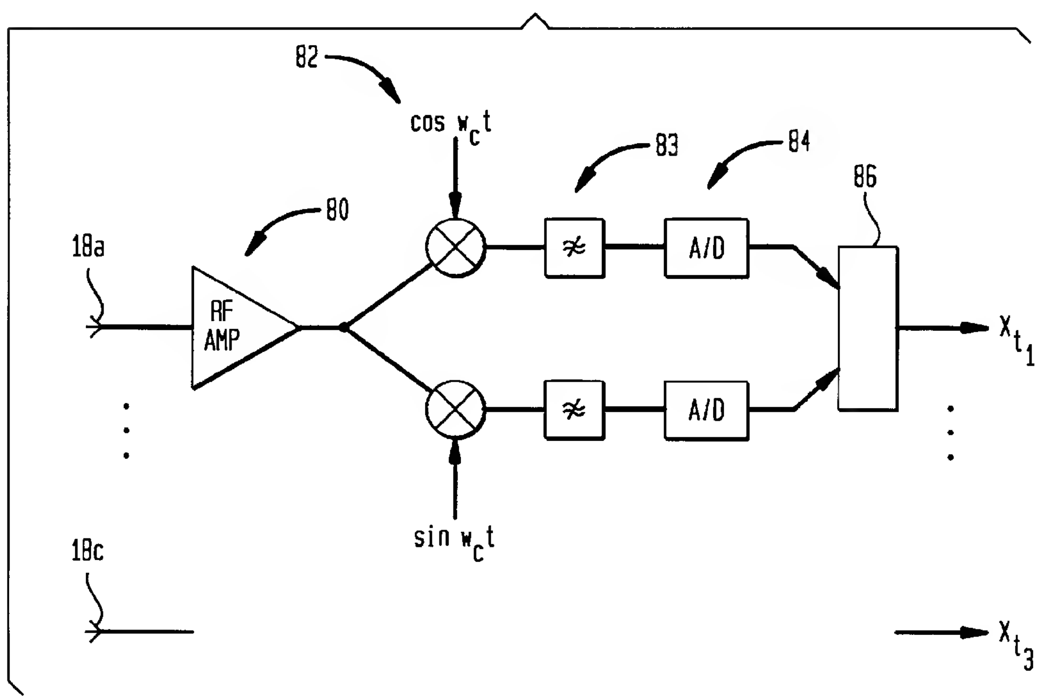

DATA SOURCE
ENCODER & MODULATOR
ENCODER & MODULATOR
ENCODER & MODULATOR
UNITARY TRANSFORMATION
TX
SVD
D
28
43
24
42
44a
44b
44c
46a
46b
46c
30
40
48a
48b
48c
16a
16b
16c
22

FIG. 5



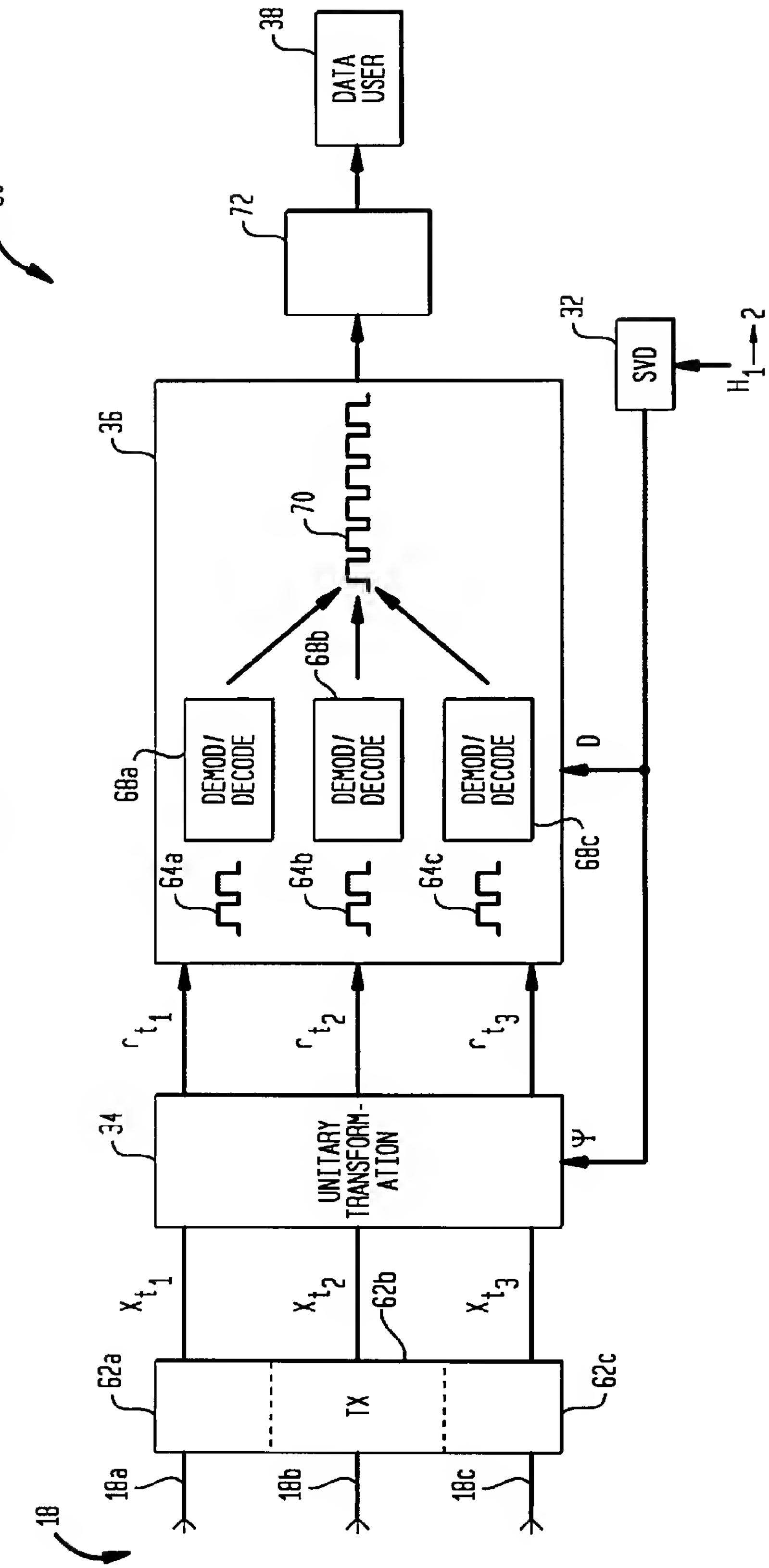
52
48
cos $w_c t$
50
51
REAL St_1
D/A
53
54
16a
S_{t_1}
RF AMP
IM. St_1
D/A
sin $w_c t$
16c
S_{t_3}

FIG. 7



82
cos $w_c t$
83
84
86
80
18a
RF AMP
A/D
A/D
X_{t_1}
sin $w_c t$
18c
X_{t_3}

FIG. 6


60
18
18a
18b
18c
62a
62b
62c
TX
X_{t_1}
X_{t_2}
X_{t_3}
34
UNITARY TRANSFORM-ATION
Ψ
r_{t_1}
r_{t_2}
r_{t_3}
36
64a
64b
64c
68a
68b
68c
DEMOD/ DECODE
DEMOD/ DECODE
DEMOD/ DECODE
D
70
72
38
DATA USER
32
SVD
$H_{1\rightarrow 2}$

MULTIPLE ANTENNA COMMUNICATION SYSTEM AND METHOD THEREOF

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to wireless communication systems and, more particularly, to a multiple antenna communication system.

2. Description of Related Art

The ultimate bit rate at which a digital wireless communication system may communicate data may be derived using Shannon's approach to information theory (commonly referred to as the Shannon limit). The ultimate bit rate is based on a number of different parameters, including: the total radiated power at the transmitter; the number of antennas at the transmitter and receiver; bandwidth; noise power at the receiver; and the characteristics of the propagation environment. For wireless transmission using multiple antennas at the transmitter and/or receiver in a so-called Rayleigh fading environment, the ultimate bit rate could be enormous, for example, hundreds of bits per second per Hz for a system employing 30 antennas at both the transmitter and receiver and experiencing an average signal-to-noise ratio of 16 dB.

A need exists for a wireless communications system which achieves high bit rates in a cost effective and relatively simple manner.

SUMMARY OF THE INVENTION

The present invention involves a communications system that achieves high bit rates over an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, by creating virtual sub-channels from the actual communications channel. The multiple antenna system creates the virtual sub-channels from the actual communications channel by using at the first and second units propagation information characterizing the actual communications channel. For transmissions from the first unit to the second unit, the first unit sends a virtual transmitted signal over at least a subset of the virtual sub-channels using at least a portion of the propagation information. The second unit retrieves a corresponding virtual received signal from the same set of virtual sub-channels using at least another portion of said propagation information.

In general, a propagation matrix of propagation coefficients characterizes the propagation of communication signals between the transmitting antenna(s) of the first unit and the receiving antenna(s) of the second unit. By knowing the propagation characteristics of the actual communications channel (multiple-antenna channel), the multiple antenna system can decompose the actual communications channel into multiple virtual sub-channels. For transmissions from the first unit to the second unit, both the first unit and the second unit obtain propagation information which characterizes the transmissions from the first unit to the second unit. In certain embodiments, the first unit obtains at least a portion of the propagation information, and the second unit obtains at least another portion of the propagation information. Using the respective portions of the propagation information, the first and second units cooperatively render the actual communications channel into virtual sub-channels, thereby achieving high bit rate or throughput in a relatively simple manner.

In certain embodiments, the first and second units obtain the propagation matrix as the propagation information for transmissions from the first unit to the second unit. Initially, the first unit and second units obtain the propagation matrix by an exchange of signals. For example, the first unit transmits training signals to the second unit. From the training signals as transmitted and the training signals as received over the actual communications channel, the propagation matrix can be determined. Once the propagation matrix is determined, each unit can perform a singular value decomposition of the propagation matrix. The singular value decomposition of the propagation matrix yields the propagation matrix as the product of three factors D, Φ and ψ^+, where D is a diagonal matrix and Φ and ψ^+ are two unitary matrices with the superscript "+" denoting a conjugate transpose. The singular value decomposition serves to diagonalize the propagation matrix. The number of nonzero diagonal elements in the diagonal matrix D corresponds to the number of parallel independent virtual sub-channels for the actual communications channel. In some embodiments, for transmissions from the first unit to the second unit, the first unit obtains at least a portion of the propagation information which includes the diagonal matrix D and the unitary matrix Φ. The first unit provides the diagonal matrix D to a channel coder/modulator to encode and modulate an incoming bit or information stream onto the independent virtual sub-channels according to the values of the diagonal matrix D to produce a virtual transmitted signal. As such the diagonal matrix D can provide relative scaling of the bit rate. The first unit then performs a unitary transformation on the virtual transmitted signal by multiplying the virtual transmitted signal with the conjugate transpose of the unitary matrix Φ to produce the actual transmitted signal.

The second unit obtains at least another portion of the propagation information which includes the unitary matrix ψ^+ and the diagonal matrix D in certain embodiments. The second unit performs a unitary transformation on the actual received signal by multiplying the actual received signal with the unitary matrix ψ to produce a virtual received signal. The multiplications at the first and second units by the unitary matrices establish a virtual channel from the actual communications channel between the virtual transmitted signal and the virtual received signal which can be treated as parallel independent virtual sub-channels. The second unit provides the diagonal matrix D to a channel decoder/demodulator to decode and demodulate the virtual received signal according to the matrix D to produce an information stream. Thus, the multiple antenna system provides high capacity by effectively providing parallel independent sub-channels within the same frequency band. The multiple antenna system also provides enhanced performance because the multiple antenna system transmits bits on the virtual sub-channels relative to the values of the diagonal matrix D, thereby the stronger virtual sub-channels are used to transmit more information.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and advantages of the present invention may become apparent upon reading the following detailed description and upon reference to the drawings in which:

FIG. **1** shows a baseband representation of a multiple antenna channel or the actual communications channel used according to the principles of the present invention;

FIG. **2** shows a baseband representation of the virtual sub-channels derived from the actual communications channel according to certain principles of the present invention;

FIG. **3** shows a block diagram of an embodiment of the multiple antenna system according to the principles of the present invention;

FIG. 4 shows a block diagram of an embodiment of a multiple antenna transmitter according to certain principles of the present invention; and

FIG. 5 shows a block diagram of a particular embodiment of the transmit circuitry for the transmitter of FIG. 4;

FIG. 6 shows a block diagram of an embodiment of a multiple antenna receiver according to certain principles of the present invention; and

FIG. 7 shows a block diagram of an embodiment of the receive circuitry of the receiver of FIG. 6.

DETAILED DESCRIPTION OF THE DRAWINGS

An illustrative embodiment of the multiple antenna communication system according to the principles of the present invention is described below as the multiple antenna communication system might be implemented to provide high bit rate and enhanced performance. The multiple antenna system accomplishes this by using multiple antenna arrays at the transmitter and/or receiver and taking advantage of the propagation characteristics obtained for the multiple-antenna channel between the antenna(s) of a first unit and the antenna(s) of a second unit. By knowing certain propagation characteristics of the actual communications channel (multiple-antenna channel) at the first unit and the second unit, the multiple antenna system can achieve high bit rates by having the first unit and second unit cooperatively decompose the actual communications channel into multiple virtual sub-channels. For transmissions from the first unit to the second unit, the first and second units obtain at least respective portions of the propagation information characterizing the transmissions from the first unit to the second unit. The first and second units use at least their respective portions of the propagation information to decompose the actual communications channel into multiple virtual sub-channels over which communication signals are transmitted. As such, the multiple antenna communication system achieves high bit rates in a relatively simple manner without increasing total power or bandwidth by using the virtual sub-channels within the same frequency band. Additionally, the multiple antenna system provides enhanced performance by transmitting more bits over the stronger sub-channels as determined by the propagation information.

FIG. 1 shows a baseband representation for an actual communications channel **10** over which a first unit **12** transmits the RF signals corresponding to the components s_{t1}, s_{t2} and s_{t3} of an actual transmitted signal on carriers of the same frequency over respective multiple antennas **16***a–c* to a second unit **14**. In this particular embodiment, the first unit **12** has three antennas **16***a–c*, and the second unit **14** has three antennas **18***a–c*. The second unit **14** receives the RF signals at the respective receive antennas **18***a–c* corresponding to the components x_{t1}, x_{t2} and x_{t3} of the actual received signal. Each receive antenna **18***a–c* responds to each transmit antenna **16***a–c* through a complex-valued, scalar propagation coefficient h_{mn}, where m designates the respective transmit antenna **16***a–c* and n designates the respective receive antenna **18***a–c*. As such, the actual received signal x_{t1}, x_{t2} and x_{t3} can be characterized by the following:

$$x_{t1}=h_{11}\times s_{t1}+h_{21}\times s_{t2}+h_{31}\times s_{t3}+w_{t1}$$

$$x_{t2}=h_{12}\times s_{t1}+h_{22}\times s_{t2}+h_{32}\times s_{t3}+w_{t2}$$

$$x_{t3}=h_{13}\times s_{t1}+h_{23}\times s_{t2}+h_{33}\times s_{t3}+w_{t3},$$

where $\{w_{t1}, w_{t2}, w_{t3}\}$ are receiver noise added at the second unit **14**. In vector notation, $\underline{x}_t=\underline{s}_t\times H+\underline{w}_t$ where $\underline{x}_t=[x_{t1}, x_{t2}, x_{t3}]$, $\underline{s}_t=[s_{t1}, s_{t2}, s_{t3}]$, $\underline{w}_t=[w_{t1}, w_{t2}, w_{t3}]$, and the propagation matrix can be represented as:

$$H=\begin{matrix} h11 & h12 & h13 \\ h21 & h22 & h23 \\ h31 & h32 & h33 \end{matrix}.$$

In this particular embodiment, the second unit **14** can transmit signals in the reverse direction to the first unit **12**. The second unit **14** can use its receive antennas **18***a–c* to transmit the signals, and the first unit **12** can use its transmit antennas **16***a–c* to receive the signals. If the same frequency is used in both directions (using a time division duplex (TDD) scheme in certain bi-directional communications embodiments), the propagation coefficients for transmissions from the second unit **14** to the first unit **12** can be considered equal to the propagation coefficients for transmissions from the first unit **12** to the second unit **14** (according to the reciprocity principle), so $H_{2to1}=H^T_{1to2}$, where the superscript "T" denotes the transpose. If different frequencies are used in both directions (using a frequency division duplex scheme), the propagation coefficients for the signals propagating in both directions are determined. Using an appropriate training and set-up scheme, the first unit **12** and the second unit **14** can both learn the first unit **12** to second unit **14** propagation coefficients and the second unit **14** to first unit **12** propagation coefficients. For example, the units **12** and **14** could transmit known training signals over one antenna at a time and/or transmit training signals using orthogonal signals transmitted simultaneously over all respective antennas.

For ease of discussion, the multiple antenna scheme according to the principles of the present invention is discussed with particular reference to transmissions from the first unit **12** to the second unit **14**. It should be understood that the multiple antenna scheme can be applied to both uni-directional or bi-directional communications. In this particular embodiment, both units **12** and **14** perform a singular value decomposition (SVD) of the 3×3 propagation matrix H obtained by both units **12** and **14**. In this particular embodiment, the SVD of H yields $H=\Phi\times D\times\psi^+$, where D is a 3×3 real-valued, nonnegative, diagonal matrix,

$$D=\begin{matrix} d11 & 0 & 0 \\ 0 & d22 & 0 \\ 0 & 0 & d33 \end{matrix},$$

and Φ and ψ^+ are 3×3 complex unitary matrices with the superscript "+" denoting the "conjugate transpose." The columns of a unitary matrix have unit length and are mutually orthogonal. Multiplying a vector by a unitary matrix does not change the length of the vector but merely changes the direction of the vector. The inverse of a unitary matrix is equal to the conjugate transpose of the matrix, for example, $\Phi^+\times\Phi=I$ or for l=1 to 3, $\Sigma\Phi_{1i}{}^*\times\Phi_{1j}$ is equal to 1 if i=j and is equal to 0, if i≠j, where the superscript "*" denotes the "complex-conjugate."

The second unit **14** uses the matrix ψ to multiply the received signal $\underline{x}_t$ by the 3×3 unitary matrix ψ to obtain $\underline{r}_t=[r_{t1}, r_{t2}, r_{t3}]=\underline{x}_t\times\psi$. The first unit **12** uses the matrix Φ to transform the virtual transmitted signal $\underline{y}_t$ into the actual transmitted signal $\underline{s}_t$ by letting the actual transmitted signal $\underline{s}_t$ be equal to the conjugate transpose of the 3×3 unitary matrix Φ times the virtual transmitted signal $\underline{y}_t$, $\underline{s}_t=\underline{y}_t\times\Phi^+$ where $\underline{y}_t=[y_{t1}, y_{t2}, y_{t3}]$. The multiplications by the unitary matrices are invertible operations, so there is no loss of

information. In effect, a link is established between the virtual transmitted signal $\underline{y}_t$ and the virtual received signal $\underline{r}_t$, where

$$\begin{aligned} \underline{r}_t = \underline{x}_t \times \psi &= (\underline{s}_t \times H + \underline{w}_t) \times \psi \\ &= (\underline{y}_t \times \Phi^\dagger \times H + \underline{w}_t) \times \psi \\ &= \underline{y}_t \times \Phi^\dagger \times H \times \psi + \underline{w}_t \times \psi \end{aligned}.$$

Substituting $H=\Phi\times D\times\psi^+$ in the above expression gives:

$$\begin{aligned} \underline{r}_t &= \underline{y}_t \times \Phi^\dagger \times (\Phi \times D \times \psi^\dagger)\psi + \underline{w}_t \times \psi \\ &= \underline{y}_t \times D + \underline{v}_t, \text{ where } \underline{v}_t = \underline{w}_t \times \psi \end{aligned}.$$

Thus, the original link **10** between $\underline{s}_t$ and $\underline{x}_t$ is equivalent to a much simpler virtual link **20** between $\underline{y}_t$ and $\underline{r}_t$ as shown in FIG. **2**. In the actual communications channel, every one of the N receiver antennas responds to every one of the M transmitter antennas. The advantage of the virtual link or channel **10** is that it comprises virtual sub-channels, wherein each of a plurality of virtual receiver antennas responds to exactly one respective virtual transmitter antenna. In effect, the cross-coupled actual communications channel **10** of FIG. **1** can be treated as the three parallel, independent virtual sub-channels d_{11}, d_{22} and d_{33} shown in FIG. **2** according to the principles of the present invention.

The first and second units **12** and **14** can determine the respective propagation information needed to establish the virtual sub-channels between the first unit **12** and the second unit **14** in alternative ways. For example, since the matrix $HH^+=\Phi\times D\times D^+\times\Phi^+$, the first unit **12** and/or the second unit **14** can determine the unitary matrix Φ^+ from the eigenvectors of the matrix HH^+ and the diagonal matrix D from the eigenvalues of HH^+. Additionally, since $H^+H=\psi\times D^+\times D\times\psi^+$, the first unit **12** and/or the second unit **14** can determine the unitary matrix ψ from the eigenvectors of H^+H and the diagonal matrix D from the eigenvalues of H^+H. The diagonal matrix can be determined by using the squareroots of the eigenvalues of HH^+ or H^+H.

FIG. **3** shows an embodiment of the multiple antenna communication system according to certain principles of the present invention for transmissions between the first unit **12** and the second unit **14**. In this particular embodiment, the first unit **12** is shown as transmitting, and the second unit **14** is shown as receiving. For transmissions in the reverse direction, the first unit **12** would typically include receiver components (not shown) as will be described below for the second unit **14**, and the second unit **14** would typically include transmitter components (not shown) as described below for the first unit **12**. In accordance with certain embodiments of the present invention, the first unit **12** uses the multiple antenna array **16** for transmitting and receiving communication signals, and the second unit **14** use the multiple antenna array **18** for transmitting and receiving communication signals.

In this particular embodiment for transmissions from the first unit **12** to the second unit **14**, the propagation of the signals over the actual communications channel **10** has a baseband characterization that comprises a matrix of complex-valued (having real and imaginary parts) propagation coefficients between the transmitting antennas **16***a–c* and the receiving antennas **18***a–c*. In this particular embodiment, the first unit **12** and the second unit **14** learn the values of the propagation matrix and determine the appropriate propagation information to establish the virtual sub-channels between the first unit **12** and the second unit **14**. Alternatively, the first unit **12** and/or the second unit **14** do not learn the propagation matrix. Instead, the units **12** and **14** obtain and/or determine some portion of the propagation information, such as the diagonal matrix D, and the first unit **12** obtains and/or determines other propagation information, such as the unitary matrix Φ^+ while the second unit **14** obtains and/or determines the unitary matrix ψ.

To learn the propagation matrix (or derive the appropriate propagation information for certain embodiments) for communications from the first unit **12** to the second unit **14**, the first unit **12** can send training signals to the unit **14** from which the unit **14** determines or estimates the propagation matrix (or propagation information). The unit **14** can then send the propagation matrix (or propagation information) to the unit **12** by using a conventional communication scheme employing one or multiple antennas at the first and second units **12** and **14**. Alternatively, the unit **14** can send the propagation matrix (or propagation information) to the unit **12** using other communication links, such as a phone line. Additionally, the unit **14** can simply send back to the unit **12** the training signals received from the unit **12**, and the unit **12** determines the propagation matrix (or propagation information). The unit **12** then sends the propagation matrix (or propagation information) to the unit **14**.

Likewise, to learn the propagation matrix (or propagation information) for signals propagating from the unit **14** to the unit **12**, the unit **14** sends training signals to the unit **12** from which the unit **12** determines or estimates the propagation matrix (or propagation information). Once again, as discussed for determining the propagation matrix (or propagation information) for transmissions from the unit **12** to the unit **14**, the unit **12** can provide and/or derive different forms or amounts of propagation information to the unit **14** depending on the particular embodiment and using different communication schemes.

Two-way transmissions between the unit **12** and the unit **14** can be accomplished using a variety of schemes, such as time division duplex (TDD) or frequency division duplex (FDD). TDD has the advantage that the channel characteristics for signals propagating from the first unit **12** to the second unit **14** are generally the same as the channel characteristics for signals propagating from the second unit **14** to the second station **12**. In the case of TDD, both units **12** and **14** occupy the same frequency band. As such, the propagation matrix for transmissions from the first unit **12** to the second unit **14** are considered transposes of each other due to the principle of reciprocity as described in D. S. Jones, "Acoustic and Electromagnetic Waves," Oxford University Press, 1989, pp. 63–64 and no further exchange of training signals is required (although updates to the propagation matrix or to propagation information can be performed). In FDD for certain embodiments, the second unit **14** transmits to the first unit **12** the propagation matrix (or propagation information) for transmissions from the first unit **12** to the second unit **14**. Additionally, after the appropriate set-up or training scheme is performed for transmissions from the second unit **14** to the first unit **12**, the first unit **12** can transmit to the second unit **14** the propagation matrix (or propagation information) for transmissions from the second unit **14** to the first unit **12**.

With particular reference to FIG. **3**, since the first and second units **12** and **14** know the propagation matrix (or propagation information which can be derived from the propagation matrix or propagation information which can be used to derive the propagation matrix or other propagation information), the units **12** and **14** can effectively decompose

the complicated multiple-antenna channel **10** into multiple independent virtual sub-channels using the propagation matrix (or respective propagation information). In this particular embodiment, the units **12** and **14** derive the multiple virtual sub-channels from the multiple-antenna channel **10** by using propagation information derived from a singular value decomposition of the propagation matrix. After learning the propagation matrix for transmissions from the first unit **12** to the second unit **14**, the first unit **12** provides the propagation matrix H to a singular value decomposition block **22**. The singular value decomposition **22** performs a singular value decomposition of the propagation matrix H which produces some propagation information, including the diagonal matrix D and two unitary matrices Φ and ψ^+ where the superscript $^+$ denotes a conjugate transpose. The number of nonzero diagonal elements in the matrix D represents the number of parallel independent virtual sub-channels.

For transmissions from the first unit **12** to the second unit **14** in this particular embodiment, the first unit **12** provides the diagonal matrix D to a channel coder/modulator **24** to encode and modulate an incoming information stream from an information source **28**. The channel coder/modulator **24** encodes and modulates the information stream to form a plurality of sub-information streams depending on the nonzero values of the diagonal matrix D to produce the virtual transmitted signal. The virtual transmitted signal can be represented as a vector, the respective components of which are transmitted onto respective virtual sub-channels. In this particular embodiment, a unitary transformation block **30** performs a unitary transformation on the virtual transmitted signal by multiplying the virtual transmitted signal with the conjugate transpose of the unitary matrix Φ. Finally, the first unit **12** uses the results of the unitary transformation **30** to produce the baseband version of the actual transmitted signal.

In this particular embodiment, the second unit **14** also provides the propagation matrix H to a singular value decomposition **32** and uses the results from the singular value decomposition **32** to perform a unitary transformation **34** on the actual received signal. In this particular embodiment, the unitary transformation block **34** multiplies the actual received signal with the unitary matrix ψ to produce a virtual received signal. In this particular embodiment, the multiplications by the unitary matrices at the unitary transformations **30** and **34** tend not to amplify noise and are invertible operations, so information should not be lost. The multiplications by the unitary matrices establishes a link, which can be treated as parallel independent virtual sub-channels, between the virtual transmitted signal at the first unit **12** and the virtual received signal at the second unit **14**. The second unit **14** provides the diagonal matrix D to a channel demodulator/decoder **36** which uses the diagonal matrix D to decode and demodulate the virtual received signal vector to form a single information stream which corresponds to the information stream provided to the channel coder/modulator **24** at the first unit **12**. Additionally, the first unit **12** can use the diagonal matrix D to provide enhanced performance by sending more bits on the stronger virtual sub-channels according to the nonzero values of the diagonal matrix. If the amplitude of a nonzero value of the matrix D is below a certain level, the multiple antenna system can advantageously not use the corresponding virtual sub-channel, thereby a subset of the stronger virtual sub-channels can be used. As such, the multiple antenna system achieves higher data rates in a narrow bandwidth by effectively providing parallel independent virtual sub-channels within the same frequency band and enhanced performance.

FIG. **4** shows a block diagram of a transmitter **40** having the multiple antenna array **16** with three antennas **16***a–c* for use in any unit **12** or **14** according to the principles of the present invention. For ease of discussion, the transmitter **40** will be described as being included in the unit **12** (FIG. **3**) because the multiple-element antenna communication system according to the principles of the present invention has been described in the context of transmissions from the first unit **12** (FIG. **3**) to the second unit **14** (FIG. **3**). The units **12** and **14** (FIG. **3**) in this particular embodiment, however, can both transmit and receive signals according to the principles of the present invention. In doing so, the units **12** and **14** exchange training signals to estimate the propagation matrices (or propagation information which can be the actual training signals in certain embodiments) for communications between them. After learning the propagation matrix H for signals propagating from the first unit **12** (FIG. **3**) to the second unit **14** (FIG. **3**), the transmitter **40** provides the propagation matrix H to the singular value decomposition block **22**.

The singular value decomposition block **22** performs a singular value decomposition of the propagation matrix H (which can be done for any H) to yield $H=\Phi\times D\times\psi^+$, where D is a real-valued, non-negative, diagonal matrix and Φ and ψ^+ are unitary matrices. The number of nonzero diagonal elements is less than or equal to the smaller of the number of antennas **16** at the transmitter **40** and at the second unit **14** (FIG. **3**) and represents the number of parallel independent virtual sub-channels that are available within the same frequency band. Additionally, the sizes of the nonzero diagonal elements indicate the relative signal-to-noise ratios of the virtual sub-channels. In accordance with an aspect of the present invention, the transmitter **40** allocates power to the virtual sub-channels depending on the relative signal-to-noise ratios of the sub-channels as determined by the values of the nonzero diagonal elements of the diagonal matrix D. Thus, the better sub-channels can get more transmitter power and carry more data. In accordance with particular embodiments of this aspect of the present invention, the transmitter **40** has a total power restriction and generally allocates power to the different sub-channels to provide a higher, reliable bit rate. In doing so, the transmitter **40** can allocate power to the different subchannels using a version of a Water Pouring algorithm as disclosed by Robert G. Gallager, "Information Theory and Reliable Communication," John Wiley & Sons, 1968, pp. 343–345.

The transmitter **40** receives information signals from the information source **28**, and the information stream is input into a buffer **43**. According to certain aspects of the present invention, if all of the non-zero diagonal elements of the diagonal matrix D are equal or relatively similar in this particular embodiment, the channel coder/modulator **24** can direct the first bit of a bit stream **42** from the buffer **43** to encoder/modulator **44***a*, the second bit of the bit stream **42** to encoder/modulator **44***b*, and the third bit of the bit stream **42** to encoder/modulator **44***c*. If the amplitude of the nonzero diagonal value of the matrix D corresponding to a first virtual sub-channel is twice as large as the nonzero diagonal values of the matrix D corresponding to the second and third virtual sub-channels in this particular example, the channel coder/modulator **24** could send the first two bits of the bit stream **42** to the encoder/modulator **44***a* and the next two bits of the bit stream **42** being split between the encoder/modulator **44***b* and the encoder/modulator **44***c*. To combat the effects of noise, the channel coder/modulator **24** can use ordinary error-correcting codes of the types typically used for conventional additive Gaussian noise channels as would

be understood by one of ordinary skill in the art in combination with conventional modulation schemes, such as Quadrature Phase Shift Keying (QPSK) modulation.

In this particular embodiment, the channel coder/modulator **24** produces three signal vector components y_{t1}, y_{t2} and y_{t3} of the virtual transmitted signal. The components of the virtual transmitted signal are digital complex values which can be fixed point or floating point depending on the implementation. The three components y_{t1}, y_{t2} and y_{t3} of the virtual transmitted signal from the encoder/modulators **44**a–c are provided to the unitary transformation block **30**. The unitary transformation block performs a 3×3 matrix multiplication on the components y_{t1}, y_{t2} and y_{t3} using a unitary matrix Φ^+. The result of the unitary transformation **30** is an actual transmitted signal having components s_{t1}, s_{t2} and s_{t3} which are sent to respective transmit circuits **48**a–c and converted as necessary to the radio frequency (RF) domain. In this particular embodiment, the transmit circuitry **48**a–c modulates the components s_{t1}, s_{t2} and s_{t3} of the actual transmitted signal onto the same carrier and transmits each component s_{t1}, s_{t2} and s_{t3} of the actual transmitted signal over a respective antenna **16**a–c.

FIG. **5** shows a general diagram for an embodiment of the transmit circuitry **48**. In this particular embodiment, each components s_{t1}, s_{t2} and s_{t3} of the virtual transmitted signal vector is split into real and imaginary parts by block **50**. The real and imaginary parts of each component s_{t1}, s_{t2} and s_{t3} are input to digital-to-analog converters **51**. Multipliers **52** multiply the analog real part of each component s_{t1}, s_{t2} and s_{t3} by $\cos\omega_c t$ with ω_c being the carrier frequency (radians/second) and multiply the analog imaginary part of each component s_{t1}, s_{t2} and s_{t3} by $\sin\omega_c t$. Afterward, respective real and imaginary parts of each component s_{t1}, s_{t2} and s_{t3} are added together by summers **53** to produce an RF signal for each component s_{t1}, s_{t2} and s_{t3} on the same carrier frequency ω_c. Each RF signal is then amplified by respective RF power amplifiers **54** and transmitted over respective antennas **16**a–c in this particular embodiment. Alternative embodiments for the transmit circuitry **48** are possible.

FIG. **6** shows a block diagram of a receiver **60** having the multiple antenna array **18** with three antennas **18**a–c for use in any unit **12** or **14** (FIG. **3**) according to the principles of the present invention. For ease of discussion, the receiver **60** will be described as being included in the second unit **14** (FIG. **3**) because the multiple-element antenna communication system according to the principles of the present invention has been described in the context of transmissions from the first unit **12** (FIG. **3**) to the second unit **14** (FIG. **3**). As mentioned above, the units **12** and **14** (FIG. **3**) in this particular embodiment can both transmit and receive signals according to the principles of the present invention.

As described above for this particular embodiment, the receiver **60** receives training signals from the transmitter **40** (FIG. **4**) and estimates the propagation matrix H for communications from the transmitter **40** (FIG. **4**) to the receiver **60**. After learning the propagation matrix H for signals propagating from the transmitter **40** (FIG. **4**) to the receiver **60**, the receiver **60** provides the propagation matrix H to the singular value decomposition block **32**. As in the transmitter **40** (FIG. **4**), the singular value decomposition block **32** performs a singular value decomposition of the propagation matrix H to yield $H=\Phi\times D\times\psi^+$, where D is a real-valued, non-negative, diagonal matrix and Φ and ψ^+ are 3×3 complex unitary matrices with the superscript "+" denoting the "conjugate transpose."

The receiver **60** receives the signals propagating from the transmitter **40** (FIG. **4**) through the multiple antenna array **18**, and receiver circuits **62**a–c process the signals received from the respective antennas **18**a–c down to baseband. In this particular embodiment, the actual received signal vector $\underline{x}_t$ is digitized before being provided to the unitary transformation block **34**. The unitary transformation block **34** uses its propagation information derived from the propagation matrix H to multiply the actual received signal $\underline{x}_t$ by the 3×3 unitary matrix ψ to obtain a virtual received signal $\underline{r}_t=[r_{t1}, r_{t2}, r_{t3}]=\underline{x}_t\times\psi$. The channel demodulator/decoder **36** receives the virtual received signal $\underline{r}_t$ from the unitary transformation block **34** with respective parallel components r_{t1}, r_{t2} and r_{t3}. The components r_{t1}, r_{t2} and r_{t3} are provided to respective parallel demodulators/decoders **68**a–c. The parallel demodulators/decoders **68**a–c demodulate and decode the virtual received signal $\underline{r}_t$ according to the modulation and coding scheme used by the transmitter **40** (FIG. **4**).

Using the nonzero diagonal values of the diagonal matrix D from the SVD block **32** and reflecting the use of the matrix D in the transmitter **40** (FIG. **4**), the channel demodulator/decoder **36** constructs a single stream **70** of information bits from the parallel components r_{t1}, r_{t2} and r_{t3} of the virtual received signal. As such, the diagonal matrix D used to construct the information stream **70** from the parallel streams **64**a–c in the receiver **60** is the same matrix D used to separate the single stream **42** (FIG. **4**) into parallel streams **46**a–c (FIG. **4**) in the transmitter **40** (FIG. **4**). The information stream **70** is then output to its destination **38** before which the information stream **70** can pass through additional processing or circuitry **72** which can include a data buffer.

FIG. **7** shows a general diagram for an embodiment of the receive circuitry **62**. In this particular embodiment, the transmitted RF signals from the transmit circuitry **48** (FIG. **5**) are received at the antennas **18**a–c. The RF signals received at each antenna **18**a–c are amplified by respective pre-amplifiers **80**. Multipliers **82** multiply the respective RF signals by $\cos\omega_c t$ and $\sin\omega_c t$ with ω_c being the carrier frequency to produce analog versions of the real and imaginary parts of the components of the actual received signal which were modulated onto carriers of the same frequency ω_c. The analog versions of the real and imaginary parts for each component of the actual received signal are low pass filtered by filters **83** and provided to analog-to-digital converters **84** to produce digital versions of the real and imaginary parts of each component. Combiner **86** combine the real and imaginary parts of each component to produce the components x_{t1}, x_{t2} and x_{t3} of the actual received signal as complex digital values. In this particular embodiment as described above, the components x_{t1}, x_{t2} and x_{t3} of the actual received signal are provided to the unitary transformation block **34** (FIG. **6**). The receive circuitry **62** is shown as a homodyne receiver, but alternative embodiments for the receive circuitry **62** are possible.

In accordance with certain embodiments of the present invention, the multiple antenna system updates the propagation matrix or information periodically or continuously as operating conditions change. As such, if an antenna **16** (FIG. **4**) or **18** becomes unavailable, the multiple antenna system can update the propagation matrix(ices) or information at the two units **12** and **14**, thereby maintaining the communications between the units **12** and **14** and still providing a high bit rate. Additionally, depending on the conditions of the virtual sub-channels (which can be measured by the nonzero diagonal values of the diagonal matrix D), the bit rate between the two units **12** and **14** using the multiple antenna system is scaleable. Accordingly, if the signal-to-noise ratio, virtual sub-channel gain or other measurement value for a virtual sub-channel drops below a certain threshold level

and/or a relative level compared to the other sub-channels, the multiple antenna system can either reduce the number of bits transmitted over the virtual sub-channel or drop the virtual sub-channel, thereby reducing the bit rate, until updates of the propagation matrix or information show that the virtual sub-channel has risen above the threshold level and/or the relative level. Furthermore, in similar fashion, the multiple antenna system according to certain principles of the present invention can allocate power to the different virtual sub-channels based on the conditions of the different virtual sub-channels as determined by the nonzero values of the diagonal matrix D or other measurement values corresponding to the virtual sub-channels.

The multiple antenna system enables an increase in bit rate without an increase in power or bandwidth as compared to single antenna systems. In certain embodiments, the propagation of the signals is modeled as flat fading (no frequency dependence to fading). Additionally, in the event of receiver noise and external interference, the multiple antenna system can use a covariance matrix or the like which characterizes the receiver noise and/or the external interference to effectively alter the propagation information or to include the covariance matrix or the like as part of the propagation information. If the elements of the propagation matrix H are statistically independent, identically distributed, with Rayleigh-distributed magnitude and uniformly distributed phase, the capacity of the channel grows linearly with the smaller of the number of transmitter and receiver antennas. Theoretically, there is no limit to the number of antennas that can be utilized in the multiple antenna system, thereby providing the potential for enormous capacities in a narrow bandwidth. For example, if 170 antennas are used at the transmitter and the receiver in a 30 kHz bandwidth with signal-to-noise ratios of 20 dB, 20 Mb/s of High Definition TV (HDTV) may be sent over the multiple antenna channel after being decomposed to 170 virtual sub-channels according to the principles of the present invention.

The multiple-element antenna system according to the principles of the present invention can achieve such high bit rates in the narrow bandwidth and in a simple manner by using multiple antennas at both the transmitter and receiver to decompose the multiple antenna channel into multiple independent virtual sub-channels. A pair of units using the multiple antenna system use a distinct band of frequencies for communicating with each other over the multiple-antenna channel. Thus, different pairs of units can be frequency division multiplexed. A pair of units can take a variety of forms, such as units which can handle voice and/or data in a wireless local area network. Additionally, the multiple antenna system can provide security in communications between a pair of units because the propagation information characterizing the actual communications channel between the pair of units is unique to that pair. As such, even if a third party obtained the propagation information for the pair, it would be difficult for the third party to intercept the communications between the pair because the propagation information for an actual communications channels between the third party and each of the pair of units would be different.

In addition to the embodiments described above, alternative configurations of the multiple antenna system according to the principles of the present invention are possible which omit and/or add components and/or use variations or portions of the described multiple antenna system. For example, the multiple antenna system has been described with three antennas at both the first unit and the second unit to provide three virtual sub-channels, but different numbers of antennas can be employed at the first unit and the second unit. Additionally, the multiple antenna system has been described as being employed in terms of communications over a multiple antenna channel from the first unit to the second unit. The multiple antenna system, however, includes units which transmit and/or receive according to the principles of the present invention. In certain embodiments, the units use the same multiple antennas for both transmission and reception. Alternative embodiments of units employing the multiple antenna system are possible, however, which use a subset of the multiple antennas for transmission and/or reception depending on the number of antennas at the unit on the other end of the multiple antenna channel or upon the values of the diagonal matrix in the reverse direction.

The above-described multiple antenna system has been described as comprising several components or blocks, but it should be understood that the multiple antenna system and portions thereof can be implemented in application specific integrated circuits, software-driven processing circuitry, or other arrangements of discrete components as would be understood by one of ordinary skill in the art with the benefit of this disclosure. What has been described is merely illustrative of the application of the principles of the present invention. Those skilled in the art will readily recognize that these and various other modifications, arrangements and methods can be made to the present invention without strictly following the exemplary applications illustrated and described herein and without departing from the spirit and scope of the present invention.

We claim:

1. A method for transmitting communication signals, said method comprising:

sending by a first unit a virtual transmitted signal over at least a subset of virtual sub-channels of an actual communications channel using at least a portion of propagation information characterizing said actual communications channel between M transmitter antennas of said first unit and N receiver antennas of a second unit, where M or N>1.

2. The method of claim **1** further comprising:

transmitting by said first unit training signals to said second unit; and

obtaining said at least a portion of said propagation information by said first unit from said second unit.

3. The method of claim **1** further comprising:

transmitting by said first unit training signals to said second unit; and

obtaining by said first unit training signals as received at said second unit for determining said at least a portion of said propagation information.

4. The method of claim 1 wherein said sending further including:

transforming said virtual transmitted signal into an actual transmitted signal using said at least a portion of said propagation information; and

transmitting said actual transmitted signal over said M transmitter antennas onto said actual communications channel.

5. The method of claim **4** wherein said transmitting further including:

transmitting each component of said actual transmitted signal using a respective one of said M transmitter antennas.

6. The method of claim **4** further including:

producing a unitary matrix from said at least a portion of said propagation information.

7. The method of claim 6 wherein said producing further includes:

performing a singular value decomposition of a propagation matrix H which characterizes said actual communications channel.

8. The method of claim 6 wherein said producing further including:

using eigenvectors of a matrix derived from a propagation matrix H which characterizes said actual communications channel.

9. The method of claim 6 further including:

using said unitary matrix to perform a unitary transformation of said virtual transmitted signal into said actual transmitted signal; and

transmitting each component of said actual transmitted signal onto carriers having the same frequency.

10. The method of claim 1 further including:

receiving by the first unit an information stream from an information source; and

separating said information stream into a plurality of signal streams using at least a portion of said propagation information to form said virtual transmitted signal.

11. The method of claim 10 further including:

producing a diagonal matrix D from at least said portion of said propagation information with the nonzero diagonal values corresponding to said virtual sub-channels of said actual communications channel.

12. The method of claim 11 wherein said producing further includes:

performing a singular value decomposition of a propagation matrix H which characterizes said actual communications channel.

13. The method of claim 12 wherein said producing further including:

using squareroots of eigenvalues of a matrix derived from a propagation matrix H which characterizes said actual communications channel.

14. The method of claim 10 wherein said separating further including:

using values of a diagonal matrix D from at least said portion of said propagation information to separate said information stream into a plurality of signal streams according to said values of said diagonal matrix D.

15. The method of claim 14 further including:

using said values of said diagonal matrix D to allocate power for transmitting each component of said virtual transmitted signal.

16. A method of receiving communication signals, said method comprising:

retrieving by said second unit a virtual received signal from at least a subset of virtual sub-channels of an actual communications channel using at least a portion of propagation information characterizing said actual communications channel between M transmitter antennas of a first unit and N receiver antennas of said second unit, where M or N>1 and said first unit includes at least a portion of said propagation information.

17. The method of claim 16 further comprising:

receiving by said second unit training signals from said first unit; and

determining said at least a portion of said propagation information by said second unit using said training signals received by said second unit.

18. The method of claim 16 further comprising:

receiving by said second unit training signals from said first unit; and

sending training signals as received by said second unit to said first unit;

determining by said first unit said at least a portion of said propagation information using said training signals as received by said second unit; and

sending said at least a portion of said propagation information by said first unit to said second unit.

19. The method of claim 16 wherein said retrieving further including:

receiving an actual received signal from said actual communications channel on said N receiver antennas; and

transforming said actual received signal into said virtual received signal using said at least a portion of said propagation information.

20. The method of claim 19 wherein said retrieving further including:

receiving each component of said actual received signal using a respective one of said N receiver antennas.

21. The method of claim 19 further including:

producing a unitary matrix from said at least a portion of said propagation information.

22. The method of claim 21 wherein said producing further includes:

performing a singular value decomposition of a propagation matrix H which characterizes said actual communications channel.

23. The method of claim 21 wherein said producing further including:

using eigenvectors of a matrix derived from a propagation matrix H which characterizes said actual communications channel.

24. The method of claim 21 further including:

receiving each component of said actual received signal from carriers having the same frequency; and

using said unitary matrix to perform a unitary transformation of said actual received signal into said virtual received signal.

25. The method of claim 16 further including:

combining components of said virtual received signal to provide an information stream using at least a portion of said propagation information.

26. The method of claim 25 wherein said combining further including:

producing a diagonal matrix D from at least said portion of said propagation information.

27. The method of claim 26 wherein said producing further includes:

performing a singular value decomposition of a propagation matrix H which characterizes said actual communications channel.

28. The method of claim 26 wherein said producing further including:

using squareroots of eigenvalues of a matrix derived from a propagation matrix H which characterizes said actual communications channel.

29. The method of claim 25 wherein said combining further including:

using values of a diagonal matrix D from at least said portion of said propagation information to combine said virtual received signal into an information stream according to said values of said diagonal matrix D.

30. A method of communicating over an actual communications channel, said method comprising:

creating virtual sub-channels from said actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, by using at said first unit and said second unit propagation information characterizing said actual communications channel;

sending by said first unit a virtual transmitted signal over at least a subset of said virtual sub-channels using at least a portion of said propagation information; and

retrieving by said second unit a virtual received signal from said at least a subset of said virtual sub-channels using at least another portion of said propagation information.

31. A transmitter for transmitting information signals comprising:

a plurality of antennas;

processing circuitry configured to obtain propagation information for an actual communications channel between said plurality of antennas and a plurality of receiver antennas, said processing circuitry comprising a channel coder configured to receive an information signal stream and at least a portion of said propagation information, said channel coder further configured to separate said information signal stream using said at least a portion of said propagation information to form a virtual transmitted signal of components corresponding to sub-channels of said communications channel, said processing circuitry further configured to perform a transformation on said virtual transmitted signal using at least another portion of said propagation information to form an actual transmitted signal; and

transmit circuitry coupled to said plurality of antennas and configured to transmit each component of said actual transmitted signal through a respective one of said plurality of antennas on carriers of the same frequency.

32. A receiver for receiving information signals comprising:

a plurality of antennas;

receive circuitry coupled to said plurality of antennas and configured to receive each component of an actual received signal through a respective one of said plurality of antennas; and

processing circuitry configured to obtain propagation information for a communications channel between said plurality of antennas and a plurality of transmitter antennas at a transmitter having at least a portion of said propagation information, said processing circuitry further configured to perform a transformation on said actual received signal using at least a portion of said propagation information to form a virtual received signal, said processing circuitry comprising a channel decoder configured to receive said virtual received signal and at least another portion of said propagation information, said channel decoder further configured to combine said virtual received signal into an information stream using said at least another portion of said propagation information.

33. A method for transmitting communication signals on an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, said method comprising:

producing by said first unit using at least a portion of propagation information characterizing said actual communications channel an actual transmitted signal of components for transmission over said actual communications channel to said second unit for transformation by said second unit using at least a portion of said propagation information.

34. A method of receiving communication signals from an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, said method comprising:

transforming by said second unit using at least a portion of propagation information characterizing said actual communications channel a plurality of components of an actual received signal received from said actual communications channel from said first unit after being produced at said first unit using at least a portion of said propagation information.

35. A method for transmitting communication signals, said method comprising:

creating virtual sub-channels from an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, by using at said first unit and said second unit at least portions of said propagation information characterizing said actual communications channel; and

sending by said first unit a virtual transmitted signal over at least a subset of said virtual sub-channels using at least a portion of said propagation information.

36. A method of receiving communication signals, said method comprising:

creating virtual sub-channels from an actual communications channel between M transmitter antennas of a first unit and N receiver antennas of a second unit, where M or N>1, by using at said first unit and said second unit at least portions of said propagation information characterizing said actual communications channel; and

retrieving by said second unit a virtual received signal from at least a subset of said virtual sub-channels using at least a portion of said propagation information.

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